Silicon-based Polarization-insensitive Optical Antenna

Design and Experimental Characterization of Optical Phased Arrays

By

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Abstract

Optical Phased Array (OPA) that operates within the optical wavelength range (400nm – 1550nm) has emerged as one of the most popular technologies in recent years with the advancement of integrated photonics industry. The integration of optoelectronics components on-chip allows the OPA to steer the beam to achieve ranging, detection, and free-space communication without having any moving parts.

The thesis includes two parts. Firstly, a polarization-independent optical surface grating antenna designed for OPA is presented. The designed antenna emits both quasi-transverse electric (TE) and quasi-transverse magnetic (TM) modes towards the same angle with similar beamwidth. With the increasing demanding for mode-division multiplexing systems, the incorporation of such antenna in an OPA system allows an additional channel of data transmission while preserving the steerability of the array. In the second part of the thesis, the optical testing setup for a fabricated on-chip OPA system is designed and presented. With the testing setup designed and assembled, a comparison between the observed and simulated far-field images is also presented.
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List of Abbreviations

OPA: Optical Phased Array

FDTD: Finite-Difference Time-Domain

EME: Eigen Mode Expansion

FEM: Finite-Element Method

RCWA: Rigorous Coupled-Wave Analysis

RCWA-LW: Rigorous Coupled-Wave Analysis – Leaky Wave

EM: Electromagnetic

SOI: Silicon on Insulator

SWG: Subwavelength Grating

MMI: Multimode Interferometer

TE: Transverse Electric

TM: Transverse Magnetic

BOX: Buried oxide

TOX: Top Oxide

PIC: Photonics Integrated Circuit

CMOS: Complementary Metal Oxide Semiconductor

FSO: Free-Space Optical

LIDAR: Light Detection and Ranging

MEMS: Microelectromechanical System

IR: Infrared

NIR: Near-Infrared

AR: Anti-Reflection
Chapter 1 Introduction

1.1 Silicon Photonics

Integrated photonics studies the generation, transmission, and detection of light on chip-scale semiconductor materials such as indium phosphate, gallium arsenide, and silicon. People have studied the feasibility to guide and manipulate light in silicon since 1980s. In the following thirty years, many of proof-of-concepts silicon-based photonics components, which together act as the building blocks of silicon photonics have been realized. Some of the most important building blocks are silicon-based on-chip laser, waveguide, and modulators [1]. These components work together to deliver a fast optical interconnect with bandwidth up to Tb/s.

However, the popularity of silicon photonics technology did not solely come from its fast data bandwidth but also due to its compatibility with complementary-metal-oxide-semiconductor (CMOS) fabrication process, for which the industry has invested both time and money in. CMOS process did not only provide easy photonics fabrication, but also allowed the monolithic integration of photonics and electronics components on the same chip, which paved way for transitioning to photonics technology for telecommunication industry [2].

Most of the silicon photonics components are fabricated on silicon-on-insulator (SOI) wafer. As shown in Figure 1, a typical SOI waveguide consists of three layers: silicon substrate layer, buried oxide (BOX) layer and silicon core layer. An upper cladding layer made of silicon dioxide is optional depending on the design. At 1550nm telecom wavelength, silicon and silicon oxide have refractive indices of 3.476 and 1.444.
respectively. The large index contrast allows the tight confinement of mode inside silicon waveguide, which in turn reduces the device footprint.

![Figure 1 Schematic of SOI rib waveguide and mode profile [3]](image)

Besides, silicon has a transparency window at telecom wavelength, most importantly at 1310nm and 1550nm. This allows silicon photonics components to be easily designed to work under telecom environment. As an optically guiding material, silicon has also been proven to have nonlinear effect. This has allowed the realization of supercontinuum generation and frequency comb on silicon platform [4]. Together with the high-bandwidth, ease of fabrication and monolithic integration with electronics, silicon photonics has proven itself to be a good candidate in the field of integrated photonics.

1.2 Background

Figure 2 shows front view of a typical SOI planar waveguide. Light travels along z axis in the upper silicon core. Buried oxide (BOX) serves as an insulating layer to confine the light in the core silicon region due to the large refractive index contrast between silicon and silicon dioxide. The silicon substrate serves as a foundation to provide mechanical stability. Light travels in the waveguide in different modes. Modes are allowed electrical and magnetic field distribution inside waveguide -- silicon, in this case. Depending on the
polarization of propagating light, the modes can be classified into two categories: TE (Transverse Electric) and TM (Transverse Magnetic) modes. As the names suggest, TE modes are the modes with electric field distribution transverse (perpendicular) to the plane of incidence (y-z plane). TM modes however are the ones with magnetic field distribution transverse to the plane of incidence. Depending on the dimension, a waveguide can support more than one TE or TM modes. However, most of the PICs are designed with fundamental modes only given the existence of mode crosstalk and multimode interference [5].

![Figure 2 Sideview of SOI planar waveguide](image)

The characteristic of a mode propagating inside a waveguide can be described by the mode’s effective index $n_{\text{eff}}$. It describes the relative spatial frequency $k$ of a corresponding mode as well as its group velocity $v_g$.

$$k = n_{\text{eff}} \frac{2\pi}{\lambda_0}$$

In equation 1.1, $\lambda_0$ is the wavelength of the light in free space. This number is typically 1310nm or 1550nm when we work in the telecom wavelength. $k$ describes how
much oscillation a light wave has in each spatial period, which has led to its name spatial frequency.

\[ v_g = \left( \frac{\partial k}{\partial \omega} \right)^{-1} \]  

Equation 1.2 describes the group velocity of a narrow-band pulse, which is determined by its wavevector \( k \). We typically care more about the group velocity than phase velocity for a propagating mode due to chromatic dispersion.

Because silicon slab waveguide width is much larger than its thickness, and the BOX is a good insulator which prevents the mode leakage into the substrate, the effective index of the mode can be approximated using 1-D approach with bottom silicon substrate omitted [6].

![Figure 3 1-D approximation diagram of waveguide](image)

Two dispersion equations for TE and TM modes can be expressed as equation 1.3 and 1.4:
\[ V \sqrt{1 - b} = \tan^{-1} \left( \frac{a + b}{\sqrt{1 - b}} \right) + \tan^{-1} \left( \frac{b}{\sqrt{1 - b}} \right) + m\pi \quad (1.3) \]

\[ V \sqrt{1 - b} = \tan^{-1} \left( \frac{1}{d} \sqrt{\frac{a + b}{1 - b}} \right) + \tan^{-1} \left( \frac{1}{c} \sqrt{\frac{b}{1 - b}} \right) + m\pi \quad (1.4) \]

As indicated in [6], V is the normalized frequency, b is the normalized effective index, a is an indicator of the level of symmetry between upper cladding and BOX. c and d are parameters applies to TM mode specifically, which measures the ratio between waveguide core index and surrounding material. The exact mathematical definitions of these terms are:

\[ V = k * h * \sqrt{\frac{n_f^2 - n_s^2}{n_f^2 - n_s^2}} \quad (1.5) \]

\[ a = \frac{n_s^2 - n_c^2}{n_f^2 - n_s^2} \quad (1.6) \]

\[ b = \frac{n_{eff}^2 - n_s^2}{n_f^2 - n_s^2} \quad (1.7) \]

\[ c = \frac{n_c^2}{n_f^2} \quad (1.8) \]

\[ d = \frac{n_c^2}{n_f^2} \quad (1.9) \]

The h in equation 1.5 is the thickness of the waveguide. As can be seen from equation 1.8 and 1.9, c and d are determined by the material only. Therefore, they are considered as constants. \( n_s \), \( n_f \) and \( n_c \) are material refractive indices of the corresponding regions according to Figure 3. For a given waveguide thickness (h), V can be computed, then equation 1.3 and 1.4 can be solved in terms of b. From this, the effective indices of
the corresponding mode can be computed. Figure 4 shows curves of mode effective indices vs waveguide thickness. As can be seen, higher order TE and TM modes start appearing when the waveguide thickness goes above around 230nm. Therefore, to maintaining single mode operation, a 220nm-thickness is a standard waveguide thickness for SOI platform.

![Effective index curves vs waveguide thickness](image)

**Figure 4 Effective index curves vs waveguide thickness**

1.3 Simulation Tool: Ansys Lumerical

The primary software used for the antenna design simulation is Ansys Lumerical [7]. Three modules within Lumerical software suite are used: MODE, FDTD and EME. MODE is primarily used to find out the allowed propagating modes given a waveguide geometry as well as finding the effective indices of the modes for either TE or TM polarization. It simplifies the procedures introduced earlier for calculating the mode effective indices numerically. Finite-Difference Time-Domain (FDTD) is one of the many EM simulations architectures for simulating waveguide structures along with Eigenmode expansion (EME) and Finite-element method (FEM). The antenna designed in this thesis
consists subwavelength (SWG) components for effective index manipulation in the direction transverse to the direction of light propagation. Such structure cannot be simulated using EME or FEM simulation method. Figure 5 shows a sample simulation setup. The setup includes the physical geometry of the simulated structure as well as several ports to measure the propagation of EM energy.

![Sample simulation setup](image)

Rigorous Coupled Wave Analysis (RCWA) has also been shown as a promising alternative simulation method for simulating grating structure over FDTD due to its semi-analytical-based approach providing more accurate results. However, RCWA it typically used for simulating diffraction grating where periodic structures exit transverse to the direction of propagation [8]. RCWA-LW (Leaky-Wave) has been proposed to simulate waveguiding grating structure however this approach is limited to grating structure with small refractive contrast [9]. Therefore, FDTD remains to be the best simulation method for the proposed optical antenna.

Two approaches are used for the simulations – 2D and 3D. 2D simulation assumes homogenous medium and infinitely long along the width of the device. This method must
be used in conjunction with effective index approximation and effective medium theory of SWG structure, which is explained in detail in chapter 2. 2D simulation allows mass reduction in simulation time therefore offers a fast way for verifying device performance before fine tuning the parameters using 3D approach. In contrast, 3D simulation simulates the entire device with the mesh size specified. Simulation time increases drastically with finer mesh which lasts from hours to days. For the design in this thesis, 3D simulation is conducted in the final design stage to verify the performance.

1.4 Optical Antennas and OPA

As mentioned above, silicon-based components are crucial building blocks of silicon photonic integrated circuits. Some of the most common components are waveguides, grating couplers, directional couplers, and multimode interferometers [10]. Optical Phased Arrays (OPAs) represent a fast-growing area of research that use these photonic building blocks to perform on-chip beam steering.

The first development of phased array-based radar began in the mid 20th century [11]. Various phased array radar systems have since been realized following this initial success [12], [13]. A phased array system functions by generating arbitrary far-field radiation patterns by independently controlling the phase of antennas arranged in a periodic array [14]. By carefully engineering the interference of each antenna, the overall beam can be steered towards the desired direction.

OPAs are based on the same interference principle as phased array-based radar. However, they operate in the higher frequency optical regime rather than the RF domain. An OPA system integrates all the components similar to what phased array radar uses but
on a chip scale.

Figure 6 illustrates a diagram of an OPA system [15].

Figure 6 shows an OPA chip proposed and fabricated by a research group that contains a grating coupler input stage, several strip-shaped optical antennas that deliver a controlled far-field beam pattern and a metal heater on top of each waveguide to thermally control the phase of each antenna.

As an on-chip beam steering device, an OPA can be used in light detection and ranging (LIDAR) [16] or in free-space optical (FSO) communication systems [17]. Because of the small wavelength of light in the optical domain, a LIDAR system has much finer resolution compared to RADAR which is essential for use cases such as autonomous driving [18] and small object tracking [19]. Currently, there are commercially available LIDAR products based on micromirrors (MEMS). Compared to MEMS-based LIDAR, OPA-based solid state LIDAR can achieve a larger steering range with higher frequency because it contains no moving parts [15]. For an FSO communication system, OPA is used as both transmitter and receiver. In [17], a 10 Gbps data rate over 50m distance has been demonstrated using OPA without a focusing lens.

Optical antennas are key components in an OPA system. They are responsible for emitting the light that is confined in the waveguide into free space, or vice versa. Given the similar operation principle with a grating coupler, almost all OPAs reported so far use
grating-based optical antennas. Depending on the requirement of the OPA, antennas with different features can be designed and implemented.

Array geometry is also an important aspect of an OPA system. Earlier demonstrated OPAs use linear arrays to demonstrate on-chip beam steering such as the one shown in Figure 6. However, such design suffers from limited steering range due to closely placed grating lobes. These grating lobes are hard to avoid given the antenna spacing requirement for photonics integration. Besides, theoretically a linear array can only preform 1-D beam steering through phase control. Broadband laser source is required to perform beam steering in the other dimension through wavelength sweeping. This makes photonics integration more challenging if on-chip laser is required. An optimized array geometry such as circular array proposed in [20] can not only steer the beam in 2-D, but also shows good suppression of grating lobes even with large element spacing.

1.5 Thesis Objectives

The first objective of the thesis is to present an optimized SOI based optical antenna for OPA that emits both TE and TM polarized light from waveguide into free space at the same angle. The core of the design, which is effective index matching of both polarizations is explained through both numerical calculation and physics-based simulation. The antenna is based on traditional SOI grating structure and therefore a detailed explanation waveguide grating is conducted prior to introducing the design itself. Finally, the optimization procedures are explained which includes the number of design parameters, parameter sweeping, beamwidth and bandwidth analysis. A separately designed input stage that uses rib waveguide-based inverse taper is also presented following the antenna design itself.
The second objective of the thesis is to explain the design steps in building a functioning near-field and far-field imaging setup. The design steps include choosing a proper magnification level, determining an observation field of view, and selecting appropriate lenses. Finally, the assembly of the setup and imaging results are presented for both the near-field and far-field.

1.6 Thesis Organization

The thesis is organized into three main parts. In chapter 2, the mathematical concept behind phased array is introduced by comparing with famous Young’s double slit experiment. The mathematic expression of the phased array far-field is derived. How the spacing between the phased array emitter affects the overall far-field pattern is also explored. Following the discussion of optical phased array, the fundamental working principle of a grating coupler is examined. The relationship between the grating period and radiation angle is presented as it is an important parameter to consider during design stage. Last, subwavelength grating (SWG) metamaterial will be introduced including two methods of synthesizing the equivalent material index. Different orientations of the SWG structure are explored and corresponding material synthesis method is presented.

In chapter 3, the design process and simulation results of the proposed silicon on insulator polarization-insensitive grating antenna is presented. The geometry choice of the antenna is validated, and the effective index approximation of such geometry is showed through both numerical analysis and 2D FDTD simulation. Various optimization approaches were utilized to improve the performance metrics of the antenna. Finally, the
results of the 3D FDTD simulation are shown to compare with the 2D results and to perform a bandwidth analysis.

In chapter 4, an experimental setup that is used to characterize an OPA system is presented. Individual components are introduced. The difference between the near-field and the far-field imaging system is explained in detail, with specialized setup designed for the image capturing. Finally, the near-field and far-field images captured from the prototype testing chip using the experimental setup designed are presented.
Chapter 2 Waveguide grating and OPA Theory

2.1 Waveguide Grating Structure

Grating Theory

Antenna elements on OPA uses grating-based structure to radiate light upward into frees space. Unlike homogenous waveguide, grating introduces periodic perturbation to the waveguide geometry to change the behavior of the propagating wave. Grating structure can be engineered so that the waveguide works in three different regimes: propagation, reflection, or radiation. Which regime the device operates under is determined by the wavelength to structure pitch ratio \[ \frac{\lambda}{\Lambda} \] as plotted in Figure 7. OPA antenna element is an application of grating waveguide structure that works specifically under the radiation regime. Therefore, proper engineering of the waveguide to make sure the propagating and reflecting regime to be avoided is important.

Figure 7 Bloch mode index vs wavelength-to-pitch-ratio for different operation regimes [21]
Figure 8 illustrates a grating coupler that operates in the radiation regime. $\beta$ is the propagation constant of the mode in the grating structure. $k_c$ is the propagation constant of the diffracted wave in the upper cladding. $\theta$ is the diffraction angle. Each grating is a scattering center which brings a portion of light from in-plane to out-of-plane. Each scattering center can be thought of an antenna discussed in Chapter 2.1. As the distance between each scattering center (pitch, $\Lambda$) increases, the relative phase difference between adjacent scattering center increases. This results in the angular shift of the location where maximum interference occurs. Additionally, a larger distance between scattering centers also introduces additional diffraction orders, which are essentially grating lobes as shown in Figure 14. This trend is confirmed in Figure 9 by plotting radiation angle vs $\Lambda$.

According to [22], phase matching condition of propagating mode in a grating coupler can be written as:

$$\beta = k_0 \times n_c \times \sin \theta + pK$$

(2.1)
where \( k_0 \) is the free-space propagation constant, \( K \) is the grating wavevector, \( n_c \) is the refractive index of the upper cladding material and \( p \) is diffraction order. \( \beta \) and \( K \) can be expressed as:

\[
\beta = \frac{2\pi n_B}{\lambda_0} \tag{2.2}
\]

\[
K = \frac{2\pi}{\Lambda} \tag{2.3}
\]

where \( n_B \) is the Bloch mode index of the propagating mode. By substituting equation 2.2 and 2.3 into 2.1 and perform some simplifications, equation 2.4 can be obtained. When operating in the radiation regime, equation 2.4, also known as Bragg condition for grating coupler, governs the relationship between the upward radiation angle \( (\theta_p) \) and the \( \Lambda \) of the grating structure for different diffraction order given a fixed Bloch mode index \( (n_B) \), index of cladding \( (n_c) \) and the operating free-space wavelength \( (\lambda) \).

\[
|\sin(\theta_p)| = \left| \frac{n_B}{n_c} + \frac{p\lambda}{n_c\Lambda} \right| \leq 1 \tag{2.4}
\]

A plot of the equation 2.4 is plotted in Figure 9. Blue represents the 1\(^{\text{st}}\) order diffraction and orange represents the 2\(^{\text{nd}}\) order diffraction. As can be seen, as soon as the \( \Lambda \) goes above a certain threshold, radiation occurs. Besides, higher diffraction order starts appearing at higher \( \Lambda \) values.
Other than the above phase matching condition for radiation, that for the Bragg resonance occurs at distinctively spaced Λ values, which should be chosen properly when designing a Bragg reflector. Equation 2.5 examines the relationship between the resonance Λ and the propagating wave. From the equation the resonance happens when the Λ is at multiples (m) of half propagating wavelength.

\[ Λ = \frac{\lambda m}{2n_B} \]  

(2.5)

The three red lines in Figure 9 represents the first three Bragg resonance pitches computed from equation 2.5.

**Relationship with diffraction grating and discussion about diffraction order**

Now let’s closely compare the conventional transmissive planar diffraction grating equation below [23] (equation 2.6) and grating coupler equation above (equation 2.4). \( n' \) is the refractive index of the media containing transmitted diffracted light. \( n \) is the refractive
index of the media on the incident side of the diffracting surface, m is the diffraction order, 
d is the diffraction grating pitch.

\[
n'sin\theta_m - nsin\theta_i = -\frac{m\lambda}{d}
\] (2.6)

If we replace n’ with nc and n with nB and make \(\theta_i = 90^\circ\), then equation 2.4 and 2.6 becomes identical. This indicates that the surface grating antenna phase matching condition is identical with that of the conventional transmissive diffraction grating with normal incidence. Therefore, the diffraction pattern of the grating antenna would follow that of the diffraction grating. Again, this confirms the idea that individual grating scattering center can be thought of individual antenna spaced at certain distances.

Due to the nature of the photonics platforms, there is one key difference between diffraction grating and waveguide grating coupler, which is the 0\(^{th}\) and positive diffraction orders. If we look at equation 2.4, 0\(^{th}\) order and positive order diffraction can only exist when Bloch mode index is smaller than cladding index, which cannot be achieved in silicon waveguide due to light confinement requirement. That is why for the waveguide grating coupler (antenna) we always work within the negative diffraction order regime.

**Subwavelength Grating (SWG)**

Subwavelength grating refers to periodic grating structure with a pitch small enough that diffraction is supressed [21]. By adjusting the geometric parameters of the structure, equivalent material can be synthesized without using a different material. This adds additional degree of freedom into the design space. Depending on the axis of light
propagation, SWG can be classified into two categories: crosswise injection (along x-axis) and lengthwise (along z-axis) injection as referenced in Figure 10.

Figure 10 Side-view of grating structure

When light propagates along x axis and the structure is operating in a sub-wavelength regime (\(\Lambda\) is much smaller than the effective wavelength in the medium), the entire SWG structure can be synthesized as a single homogeneous material as described by the 0\(^{th}\) order Rytov’s formula[21]:

\[
n_\parallel^2 = \frac{w}{\Lambda} n_1^2 + \left(1 - \frac{w}{\Lambda}\right) n_2^2
\]

\[
\frac{1}{n_\perp^2} = \frac{w}{\Lambda} \frac{1}{n_1^2} + \left(1 - \frac{w}{\Lambda}\right) \frac{1}{n_2^2}
\]

where \(n_\parallel\) and \(n_\perp\) represent the synthesized equivalent homogenous material refractive index for polarization parallel and perpendicular to the surface of alternating grating layers due to the birefringence nature of the structure. For injection into the x-axis, \(n_\parallel\) is the TM mode equivalent refractive index and \(n_\perp\) is the TE mode equivalent refractive index. As a result, in a crosswise SWG structure, TE mode has a lower effective index than TM mode as what is otherwise the case for a regular slab waveguide.
0th order Rytov’s formula provides a fast estimation of the equivalent material index during the device design process. However, it is only accurate when Λ is much smaller than the operating wavelength in the deep subwavelength regime. When Λ becomes close to or even just a little smaller than the operating wavelength, 2nd order Rytov’s formula should be applied to yield a more accurate estimation [24]:

\[
n_{\perp}^{(2)} = n_{\perp} \sqrt{1 + \frac{\pi^2}{3} R^2 \frac{w^2}{\Lambda^2} \left(1 - \frac{w}{\Lambda}\right)^2 \left(n_1^2 - n_2^2\right)^2 \left(\frac{n_{\parallel}}{n_{\text{eff,\perp}}}\right)^2 \left(\frac{n_{\perp}}{n_1 n_2}\right)^4}
\] (2.9)

\[
n_{\parallel}^{(2)} = n_{\parallel} \sqrt{1 + \frac{\pi^2}{3} R^2 \frac{w^2}{\Lambda^2} \left(1 - \frac{w}{\Lambda}\right)^2 \left(\frac{n_{\parallel}^2 - n_{\perp}^2}{n_{\text{eff,\parallel}} n_{\parallel}}\right)^2}
\] (2.10)

where \(n_{\parallel}^{(2)}\) and \(n_{\perp}^{(2)}\) represents the 2nd order equivalent material index. \(n_{\text{eff,\parallel}}\) and \(n_{\text{eff,\perp}}\) represent the mode effective indices for two polarizations (\(n_{\text{eff,\perp}}\) is for TE mode and \(n_{\text{eff,\parallel}}\) for TM mode). R is the period to wavelength ratio defined as:

\[
R = \frac{n_{\text{eff}} \Lambda}{\lambda}
\] (2.11)

When the period of the grating becomes larger than the wavelength, the structure cannot be modelled as one homogenous material anymore, above equations 2.7 to 2.10 no longer apply. Instead, their overall effective index can be written as [25]:

\[
\frac{1}{n_{\text{eff}}} = \frac{w}{\Lambda * n_{\text{eff},1}} + \left(1 - \frac{w}{\Lambda}\right)/n_{\text{eff},2}
\] (2.12)

where \(n_{\text{eff},1}\) and \(n_{\text{eff},2}\) are the mode effective indices of the corresponding mode in medium n1 and n2 respectively, regardless of polarization.

This concludes the scenarios for a crosswise operation. When the grating is operating in lengthwise (light propagates along z), the approach to synthesizes the material
refractive index is very similar to the approach above. First let’s look at structure with small pitch (deep subwavelength). Because in this case, both TE and TM polarizations have electric field polarized parallel to the alternating interfaces, equation 2.7 and 2.10 will be applied to synthesize the equivalent material. When the pitch becomes larger than the operating wavelength, equation 2.13 can be used to estimate the overall effective index of the Bloch mode, this is the fundamental equation used to calculate the overall effective index in a grating coupler. Similar to equation 2.12, this equation can be applied for calculating both TE and TM polarizations.

\[ n_{\text{eff}} = n_{\text{eff},1} \frac{w}{\Lambda} + n_{\text{eff},2} \left( 1 - \frac{w}{\Lambda} \right) \]  

(2.13)

\( n_{\text{eff}} \) can also be referred to as Bloch mode index \((n_B)\). Bloch mode index is used to describe the mode effective index in a periodic structure such as photonics crystal and grating structure. The ability to calculate the equivalent material index of a SWG structure is crucial during the initial design phase as it allows fast prototyping using 2D FDTD simulation instead of time-consuming 3D FDTD simulation.

2.2 Phased Array Mathematics and Basic Concept

To understand the underlying mathematic concept of phased array, it is important to review and understand the famous Young’s double slit experiment. As shown in Figure 11, the wave propagates after the two slits can be described using wave equation. At any point on the screen, the resulting electric field is the superposition of the two waves, therefore, can be expressed as:

\[ E_{\text{total}}(\theta) = e^{-jk_1r_1} + e^{-jk_2r_2} \]  

(2.14)

where \( r_1 \) and \( r_2 \) are vectors pointing from each slit to the spot on the screen while \( k_1 \) and \( k_2 \) are the wave vector associated with each wave. Because the distance from the slit to screen
is a lot larger than the distance between slits, two wave vectors $k_1$ and $k_2$ can approximated as $k_1 = k_2 = k$. Therefore, after numerical manipulation, following equation can be derived:

$$E_{total}(\theta) = \sum_{n=1}^{2} e^{jkx_n \sin \theta}$$  \hspace{1cm} (2.15)

where $x_n$ is the distance from $n^{th}$ slit to the origin. From equation 2.15, one important characteristic can be deducted, the resulting interference is independent of the distance between the slit and screen as long as the distance is much larger than the gap between slits. The interference pattern on the screen is what to be referred as far-field interference pattern.

Individual slit is equivalent to the antennas on a phased array. The resulting far-field radiation pattern of the array is the collaborative interference created by all antennas on the array. Young’s double slit experiment is essentially a one-dimensional phased array with two antennas.

However, there are two elements that are missing from Equation 2.15. First, the radiation pattern of individual antenna affects the overall far-field pattern. Second, unlike the simple Young’s double slits experiment, as its name suggests, on-chip phased array has control over phase of individual antenna, which allows the array to steer its beam.
Considering these two elements, the final equation that describes the far-field pattern of a phased array in 3D spherical coordinate is:

\[ E_{total} = E(\theta, \phi) \sum_{n=1}^{N} A_n e^{jkx_n \sin \theta} \]  

(2.16)

where \( E(\theta, \phi) \) is the single antenna radiation pattern, which is commonly referred to as \textit{Element Factor} and defined in polar coordinate. In chapter 3, an optical antenna design will be introduced, which concerns the element factor part of the overall equation. \( A_n \) is a complex coefficient that describes the amplitude and phase of individual antenna. \( A_n \) is commonly referred to as \textit{weight}. The summation part of the equation 2.16 including the weight is typically referred to as \textit{Array Factor}. Therefore, another way of writing equation 2.16 is:

\[ E_{total} = Array \text{ Factor} (AF) \times Element \text{ Factor} (EF) \]  

(2.17)

Steerability is an important measurement of a phased array. For a 1-D array with constant spacing between antennas, steering is achieved by applying linear phase offsets to each antenna element, which is the imaginary part of weight \( A_n \). The absolute value of the weights typically remains same while linearly changing the phases. Figure 12 shows the steering of 1-D array consists of 10 antennas with a constant antenna spacing of \( \lambda/2 \). In fact, this antenna spacing is the largest antenna spacing an array can have without creating unwanted lobes, namely grating lobes, in the far-field [26]. Figure 13 and Figure 14 shows the far-field pattern of the array with antenna spacings of \( \lambda \) and \( 2\lambda \) respectively. The existence of grating lobes means multiple beams is radiating in multiple directions, which leads to less power concentrated in the main lobe. This is not desired in application such as ranging and detection. Besides, grating lobes limit the steerability since there is no
benefit to steer beyond the region in between the main lobe and grating lobe [27].

Therefore, the distance between each antenna on the chip must be kept close in order to minimize grating lobes. However, crosstalk between waveguides occurs when elements are placed too close to each other. As a result, the positions of optical interconnects and optical phased array antennas must be engineered properly.

*Figure 12 Simulated steering of the Array Factor by applying linear phase offset to the antennas. Antenna spacing is $\lambda/2$*
Figure 13 Simulated steering of the Array Factor by applying linear phase offset to the antennas. Antenna spacing is $\lambda$.

Figure 14 Simulated steering of the Array Factor by applying linear phase offset to the antennas. Antenna spacing is $2\lambda$. 
Chapter 3 Antenna design

3.1 Literature review

The design of polarization-insensitive grating antenna follows similar design principle as polarization-insensitive grating coupler, which aims to adjust the geometry of the grating structure so that TE and TM mode have the same mode effective indices. This section covers some of the state-of-the-art polarization-insensitive grating couplers and grating antenna with advanced design parameters for improved performances.

3.1.1 Polarization-insensitive grating coupler and splitter

Polarization-insensitive grating coupler on either silicon-on-insulator or using air cladding for single wavelength has been demonstrated by using SWG elements on 340nm silicon film [24], [28]. Both designs share the fundamental concept that by introducing area in which the TM mode effective index is higher than that of TE mode (SWG region), so the overall effective indices of both modes are equal. [28] used varying SWG elements to realize an apodized grating coupler for reduced modal mismatch with the coupling fiber. Apodization is preferred in designing grating coupler but not on grating antenna since there is no need for modal match with a fiber.

Figure 15 Reported Polarization-insensitive Grating Couplers (a) with air lower cladding [24], [28] and (b) normal cladding [28]
Polarization-insensitive grating coupler has also been reported to work under distinctive wavelength, to be used as beam splitter. In [29], [30], a grating coupler based on 340nm silicon film has been reported to split TE or TM mode for either 1310nm or 1550nm light into opposite direction. In [30], similar device was demonstrated but on a 220nm platform that separates the mode and wavelength into orthogonally directed waveguide. These devices seek similar design principles by matching effective indices of the modes at different operating wavelengths.

![Figure 16 Reported dual-band dual-polarization beam splitter on (a) 340nm silicon film [29] and (b) 220nm silicon film [30]](image)

3.1.2 Single polarization grating antenna

As mentioned above, a surface grating antenna works fundamentally the same as a grating coupler except that the dimension and some performance metrics are different. Here summarizes some of the reported surface antenna designs on SOI that works in single TE polarization only [31]–[34]. The proposed antennas all have compact dimension (less than 10μm x10μm) meant to reduce the effective aperture for large field-of-view (FOV). The radiation angles are all de-tuned from perfectly vertical to prevent strong back-reflection.
3.1.3 L-shaped grating coupler and grating antenna

Some of the more advanced reported grating coupler and antenna design use partial etch of silicon to create L-shaped diffracting element for improved diffraction efficiency [35], [36]. Both designs use combination of embedded SWG element and the L-shaped diffraction element to achieve high diffraction efficiency on 220nm and 300nm SOI platform respectively. Because of this, two etching steps are required for the fabrication. By using FDTD simulation, [35] has showed a 75% coupling efficiency into a single-mode SMF-28 fiber while [36] reported an antenna with 94% directionality at a compact footprint of 7.6μm x 4.5μm, both at 1550nm central wavelength.
3.1.4 Dual-polarization optical antenna

Dual-polarization grating antennas have been reported in some literatures [37]–[39]. In [37], a polarization splitting grating antenna for on-chip LiDAR application was reported. The proposed antenna uses polarization-splitting design on 220nm platform that splits the modes into orthogonally placed waveguide as introduced in section 2.3.1. The antenna emits both TE and TM modes vertically. The overall dimension of the device is about 15µm x 15µm, which is relatively more spacious compared to other existing optical antennas. The author has shown about 44% antenna diffraction efficiency for both TE and TM polarizations. [38] proposed an innovative pillar optical antenna can simultaneously supports both fundamental mode and 2nd order mode for both TE and TM polarizations. However, such design is not typically available at commercially available foundry process. [39] has proposed the designs of grating antenna which helps to extend the steering range of OPA by using both TE and TM modes. This means the proposed antenna has been intentionally designed so that the TE and TM mode do not emit to the same angle. Therefore, such design is not polarization-insensitive. The paper examined how the antenna radiation angle of both TE and TM modes change by using different waveguide thicknesses.
Figure 19 Reported dual-polarization optical antennas (a) vertical emitting antenna that splits two polarizations orthogonally [37] (b) innovative pillar antenna [38] (c) polarization multiplexing that increases steering range by using two modes [39]

3.2 Antenna geometry and design concept

The proposed polarization-insensitive optical antenna combines the L-shaped diffraction element and SWG sections to provide high diffraction efficiency and polarization-insensitive performance at the same time. This section explains in detail about the geometry of the design and how effective index is controlled through numerical calculation.
Proposed geometry

Figure 20 Proposed antenna structure

Figure 21 Side view and top view of the proposed antenna

\[
\Lambda_x = a + b + c \quad (3.1)
\]

\[
ffx = \frac{b + c}{\Lambda_y} \quad (3.2)
\]
\[ ff_{x_{etch}} = \frac{b}{b+c} \]  
\[ ff_{y} = \frac{fill_y}{\Lambda_y} \]  

Figure 20 shows a 3D view of the proposed antenna. The upper SiO2 cladding is removed here to visually display the silicon structure. Figure 21 shows side and top view of the antenna. Zoomed-in side view of a single period is shown in Figure 21 (b). Section a in orange is the SWG element. Figure 21 (c) is the top view of the antenna and (d) shows a zoomed-in picture of the top view that contains two periods only. Equation 3.1-3.4 are the definitions of parameters that will be used throughout the chapter. As explained in equation 2.11 and 2.12, the mode effective index can be adjusted by changing the fill factor of the SWG for polarization control. In this design, the \( \Lambda_y \) is fixed at 300nm for sub-wavelength operation requirement. SWG etched portion is etched down to the buried oxide layer (full etch). A broad range of mode effective index for both TE and TM mode can be synthesized by only adjusting the parameter \( ff_{y} \)

The L-shaped diffraction element refers to the structure formed by section b and section c in Figure 21 (b)&(d). L-shaped element provides a blazing effect that if designed properly can provide higher directionality than conventional design [40]. During the fabrication, this is achieved by partially etching the full thickness of the silicon block to the desired etch depth. In this work, half etch is chosen given it is the most commonly available etching process in a commercially available foundry.
Polarization-insensitive operation

Before numerically computing the polarization-insensitive operation for the L-shaped antenna structure, the methodology of computing polarization-insensitive curve is presented using a conventional partial etch grating structure that contains two sections only. The methodology is thoroughly explained in [29].

Figure 22 Sideview of a sample waveguide grating structure

Figure 22 is a simple partially etched grating on SOI with SiO₂ upper cladding. The fundamental design principle is to adjust the structural parameters such that both polarizations have identical effective index. As explained by equation 2.18, the overall Bloch mode index can be approximated as the weighted average of individual section’s effective index within a single period with respect to its geometric length. Effective indices of both SWG and etched Si sections can be obtained by using Lumerical MODE solver. For the most seen 220nm SOI platform, the thickness of SWG and Si is 220nm and 110nm respectively. By using MODE solver, at 1550nm operating wavelength, the effective index of a SWG with $f_{ffy}$ of 0.4 is 1.5392 and 1.6028 for TE and TM respectively. For the half-
etched Si, the effective index is 2.2708 and 1.5127 for TE and TM respectively. Figure 23 shows the electric field distribution of TE and TM mode in the corresponding section.

As a result, an overall Bloch mode effective index vs $ffx$ curve can be plotted for each polarization as shown in Figure 25 (a). The intersection of two lines is the polarization-insensitive operation point. At this $ffx$, both modes have identical Bloch effective index. This is the plot for $ffy = 0.35$. The variation in effective indices for both polarizations vs $ffy$ for a 300nm $\Lambda_y$ is plotted in Figure 24. At low $ffy$, TM mode has a higher effective index compared to TE mode, which can be validated by equation 2.11 and 2.12. As the fill factor becomes larger, more silicon occupies the structure compared to the silicon dioxide. As a result, the effective index for both modes becomes higher. After certain threshold, which is indicated as the intersection of two lines in Figure 24, the TE
mode effective supersedes and becomes the larger of the two. Figure 24 illustrates the ability to control the birefringence of the SWG metamaterial by changing $f_{fy}$.

![Graph showing mode effective index vs $f_{fy}$ for 300nm pitch SWG on 220nm SOI](image)

*Figure 24: Mode effective index of both fundamental TE and TM modes in the SWG section as $f_{fy}$ changes*

After computing the intersections for other $f_{fy}$ values, a polarization-insensitive curve with $f_{fy}$ vs $f_{fx}$ can be plotted as shown in Figure 25 (b). As shown, when $f_{fy}$ becomes larger than 0.56, theoretically a polarization-insensitive operation is no longer possible since $f_{fx}$ becomes negative. It can also be observed that all $f_{fx}$ are smaller than 0.08. For a typical grating with 800nm $\Lambda_x$, this indicates the smallest feature size is about 64nm, which is unacceptable for the targeted feature size. Therefore, approaches to ensure both large feature size and polarization-insensitive operation must be taken. In Figure 25 (b), larger
ffy values are not shown given that they correspond to negative ffx values at which points theoretically the polarization-insensitive operation is not possible.

For L-shaped structure, the approach is similar. Comparing to equation 2.13 that has two terms, the weighted average of the Bloch mode index can be extended to contain three terms:

\[ n_B = [n_{SWG} \times (1 - ffx)] + [n_{L\text{-etched}} \times ffx \times ffx_{etch}] + [n_{L\text{-non-etched}} \times ffx \times (1 - ffx_{etch})] \]  

(3.5)

where \( n_{L\text{-etched}} \) and \( n_{L\text{-non-etched}} \) are the effective indices of section b and c in Figure 21 (b) respectively for both TE and TM modes. However, for plotting the polarization-insensitive curve, the grating should be approximated as a periodic structure that contains two sections only. As a result, the mode effective index of the L-shaped region can be approximated as a single section by applying equation 2.18 again.

\[ n_L = n_{L\text{-etched}} \times ffx_{etch} + n_{L\text{-non-etched}} \times (1 - ffx_{etch}) \]  

(3.6)

With this approach, for each value of \( ffx_{etch} \), a distinctive polarization-insensitive curve can be obtained, which adds one additional degree of freedom to the design space.
3.3 Choice of silicon thickness

As explained in the previous section, the L-shaped diffraction element can be approximated as a single element using equation 2.18. Therefore, different $ffx_{etch}$ values would result in different equivalent element. Figure 26 illustrates two structures with a 220nm thick silicon film with same $\Lambda_x$ and $ffx$ but different $ffx_{etch}$.

![Figure 26 Sideview of proposed grating antenna with two periods for (a) $ffx_{etch} = 0.5$ (b) $ffx_{etch} = 0.7$](image)

By taking the weighted average of the effective index, an effective index of the L-shape region only (b and c sections in Figure 26) vs $ffx_{etch}$ curve can be plotted for both TE and TM polarizations as shown in Figure 27(a). The linearly decaying effective index is expected for both TE and TM mode given that as $ffx_{etch}$ gets larger, more etched region that has lower mode effective index occupies the L-shaped element, which results in the lowering of overall effective index calculated. In this case, TE mode, like a regular planar waveguide, has a higher effective index than TM mode. $ffx_{etch}$ of less than 0.2 and greater than 0.8 is not considered given the feature size requirement.
Figure 27 (a) L-shaped region effective index vs $ffx_{etch}$ (b) polarization-insensitive curves for different $ffx_{etch}$

Figure 27 (b) shows the calculated results of the polarization-insensitive curves for various geometry of L-shaped section, namely different $ffx_{etch}$ values that ranges from 0.27 to 0.75. Figure 27 (b) illustrates that the geometrical change of the L-shaped section does not affect the polarization-insensitive operation point significantly. Particularly, the $ffx$ remains low regardless of the $ffx_{etch}$ values. Therefore, it can be concluded that 220nm is not an ideal silicon thickness for designing polarization-insensitive grating antenna. By using the same approach, polarization-insensitive curve for L-shaped structure can be calculated and plotted as well as shown in Figure 28 (a). 300nm and 500nm silicon film shows significant more acceptable feature size compared to 220nm silicon film. As a result, they can be considered as potential candidates for the design in terms of feature size requirement.
Figure 28 (a) Polarization insensitive curves for three silicon thicknesses (b) Effective Bloch index corresponding to the 300nm curves in (a)

Figure 28 (b) above shows the calculated effective Bloch mode index for 300nm L-shaped design with different \( f_{\text{etch}} \) values using equation 3.5. Preliminary 2D simulations have been conducted on 300nm silicon film with L-shaped design with different \( f_{\text{etch}} \) values to verify the radiation angles of both polarizations and compare them to the calculated radiation angle.

The \( \Lambda_x \) value used in the simulation is important since that it must be within a range that avoids generating 2\(^{nd}\) order diffraction. By using equation 3.7, which is obtained by rearranging equation 2.4, a radiation angle vs \( \Lambda_x \) graph can be plotted, where \( n_B \) and \( n_c \) are the effective Bloch mode index (Table 1) and refractive index of silicon dioxide cladding \( (1.444) \) respectively. \( m \) is the diffraction order, which is -1 in this case. \( \lambda \) is the free-space operating wavelength 1550nm.

\[
\theta = \sin^{-1}\left(\frac{n_B}{n_c} + m \cdot \frac{\lambda}{n_c \Lambda_x}\right) \tag{3.7}
\]

Theoretically, the maximum and minimum index values from Figure 28 (b) should be used to generate the radiation angle vs \( \Lambda_x \) plot to find the optimum \( \Lambda_x \) for the
preliminary 2D simulation. However, for \( f_f \) smaller than 0.2 or greater than 0.8, the smallest feature size in the SWG section would be too small to be considered as candidates. As a result, two data points labelled in Figure 28 (b) with Bloch index of 1.6205 and 2.3494 respectively have been selected to estimate the optimum \( \Lambda_x \) to be used. The result is plotted in Figure 29. Figure 29 (a) shows that for a grating with Bloch index of 1.6205, 1\(^{st}\) order diffraction occurs when the \( \Lambda_x \) is between 500nm and 1000nm. \( \Lambda_x \) greater than 1000nm would generate unwanted 2\(^{nd}\) order diffraction. Figure 29 (b) shows that for a grating with Bloch index of 2.3494, the 2\(^{nd}\) order diffraction would occur with a \( \Lambda_x \) greater than 810nm. Therefore, the 800nm \( \Lambda_x \) has been selected for the simulations.

![Figure 29](image-url)

*Figure 29 Radiation angle (°) vs \( \Lambda_x \) for grating with effective index of (a) 1.6205 and (b) 2.3494*
After performing initial 2D simulations, the calculated radiation angle vs the simulated angle for both polarizations is compared and plotted in Figure 30. Two $f_{fx_{\text{etch}}}$ values 0.55 and 0.65 are showed in the plot. At lower $ffy$ values, the model is accurate in estimating the Bloch mode index of both polarizations as the lines are almost overlap with each other. At larger $ffy$ values, the calculated radiation angle is $5^\circ$-$10^\circ$ off from the simulated angle. However, both TE and TM still show polarization-insensitive performance as they deviate away from the calculated angle together. As a result, it can be concluded that the design strategy is successful in assuring the polarization-insensitive performance of the grating antenna. A simulated far-field radiation profiles for both polarizations are shown in Figure 31. The design point used to generate the far-field is labelled in blue in Figure 30 (a). Cross-validating with Figure 30, both polarizations radiate towards the same angle. It can also be noticed that TM mode has a noticeable lower far-field amplitude compared to TE mode.

![Figure 30 Calculated vs simulated radiation angle on 300nm silicon for (a) 0.55 $ff_{x_{\text{etch}}}$ and (b) 0.65 $ff_{x_{\text{etch}}}$](image-url)
Simulations on 500nm silicon film have also been performed to verify the radiation angles of both polarizations. In this case, a $\Lambda_x$ of 680nm was chosen. As Figure 32 shows, at 0.45 $ff_x_{etch}$, radiation angles of both polarizations are very close to each other, and together they follow the trend of the calculated angle. It can also be noticed that at radiation angle near $0^\circ$, TE mode radiation angle shows an obvious dip and not follow the trend. This is caused by the strong back reflection accompanied by vertical radiation ($0^\circ$), which distorts the far-field radiation profile. Vertical emission of grating is typically avoided unless certain methods such as chirped grating are implemented to reduce the back reflection [41]. 2D radiation profiles of vertical and off-vertical radiation are shown in Figure 33 to illustrate the distorted and non-distorted far-field radiation profiles. The corresponding data points used are labelled in Figure 32. Figure 33 (a) shows a distorted radiation pattern which corresponds to the data point at ffy = 0.3 in Figure 32. The distorted pattern that is intended to emit at $0^\circ$ in fact emits very little energy into the free space compared to the non-distorted one because majority of energy is reflected into the input waveguide. More so the remaining energy forms more than one main lobe therefore makes
the result meaningless. The algorithm that extracts the radiation angle picks the radiation angle that has the highest amount of radiation which explains the dip in Figure 32. Far-field profiles of both TE and TM are shown in Figure 34 to show that both polarizations are radiating towards the same angle, and each has distinctive main lobe. Based on the simulations run so far, it can be concluded that the polarization-insensitive design approach is both valid on 300nm and 500nm silicon film.

![Simulated and calculated radiation angle for L-shaped 500nm silicon with 0.45 ffx_{etch}](image)

*Figure 32 Simulated radiation angle vs calculated radiation angle for 500nm L-shaped design with 0.45 ffx_{etch}*

![2-D far-field distorted and non-distorted profile corresponding to the points in Figure 32](image)

*Figure 33 2-D far-field distorted and non-distorted profile corresponding to the points in Figure 32*
Other than radiation angle, upward radiation efficiency \( P_{\text{upward}} \) is also investigated to choose the most suitable silicon thickness. The definition of \( P_{\text{upward}} \) is shown in equation 3.8. After sweeping along the 300nm and 500nm curves shown in Figure 28 (a) the heatmaps that show \( P_{\text{upward}} \) for both TE and TM are presented in Figure 35.

\[
P_{\text{upward}} = \frac{\text{power radiated upward}}{\text{total input power}} \tag{3.8}
\]
Figure 35 clearly shows that without any optimizations, $P_{\text{upward}}$ of TE polarization on both 300nm and 500nm silicon can achieve similar performance up to 80%, which aligns with the observation made in [42], while $P_{\text{upward}}$ of TM polarization shows a significant difference between two silicon thicknesses. This result aligns with the observation made in [43] as a well-designed grating structure can only emits up to 56% of its TM-polarized mode while up to 89% of TE-polarized mode can be realized on a similar structure [36]. As a result, 500nm silicon film has been chosen over 300nm and upon which further optimizations are conducted.
3.4 Define degree of freedom and performance metrics

Before optimization starts, it is important to determine the parameters that will be used. The parameters themselves decide the physical behavior of the device and the number of parameters would have impact on the complexity of the optimization process. The parameters used are: \( ffy, ffx_{\text{etch}}, \Lambda_x, t_{\text{ROX}}, t_{\text{input}} \) and \( dc_{\text{swg\_1st}} \).

\( ffy \) and \( ffx_{\text{etch}} \) are used to examine every point on the polarization-insensitive curve as shown in Figure 35 to find the design with the best diffraction performance. According to [44], [45], the \( \Lambda_x \) not only changes the radiation angle, but also affects the directionality, which is defined in equation 3.9. This is due to the cavity effect of the buried oxide (BOX) region. This cavity effect is verified by performing a BOX thickness scan on the same design as Figure 34. A clear periodic behavior of the upward radiation as the \( \Lambda_x \) is varying can be observed. As a result, when downward radiation angle changes as \( \Lambda_x \) varies, a scan of BOX thickness can be performed to find the best BOX thickness at a given \( \Lambda_x \). Using the same design point as above, a nested parameter sweep of \( \Lambda_x \) and BOX thickness is performed and the results are shown Figure 37. Similar periodic behavior like Figure 36 can be observed by taking vertical cuts in both Figure 37 (a) and (b). Taking horizontal cuts in both figures illustrates that at a given BOX thickness, the choice of \( \Lambda_x \) significantly affects the amount of upward radiation. Therefore, \( \Lambda_x \) should be included as one of the parameters during the optimization. Besides, Figure 37 shows that for the chosen design point \( (0.45 ffx_{\text{etch}}, 0.55 ffy) \), there is not a point in the parameter space that simultaneously provide good \( P_{\text{upward}} \) for both TE and TM modes.

In our design, since the thickness of the BOX \( t_{\text{BOX}} \) is typically fixed at a wafer level, \( t_{\text{BOX}} \) is fixed at commercially available \( 3\mu m \) [46] in our design and therefore is not a
design parameter. Top cladding (TOX) forms a cavity like BOX. Therefore, the thickness of TOX ($t_{TOX}$) does affect the directionality. Because top cladding deposition is done at the last step of the fabrication, $t_{TOX}$ can be varied more easily than $t_{BOX}$ and therefore is another design parameter.

$$\text{directionality} = \frac{\text{power radiated upward}}{\text{power radiated upward} + \text{power radiated downward}}$$  \hspace{1cm} (3.9)
While trying to maximize the $P_{upward}$, it is also important to minimize the reflection at the grating and input waveguide interface. Figure 38 summarizes some of the approaches to minimize reflection from published articles: using inverse taper, adding antireflection pillar, reduce input waveguide thickness and adjusting the first SWG duty cycle to create smoother waveguide to grating effective index match. Two approaches are being verified in our design: reduce input waveguide thickness and adjusting first SWG duty cycle. As a result, $t_{\text{input}}$ and $dc_{\text{SWG}_\text{1st}}$ are the two corresponding parameters to be used when optimizing the reflection performance using two approaches respectively.

![Figure 38 Summary of antireflection approaches](image)

**Figure 38 Summary of antireflection approaches**

(a) inverse taper [47] (b) antireflection pillar [40] (c) reduce input waveguide thickness [44] (d)-(f) adjust first SWG geometry [36], [48], [49]

### 3.5 Optimization process and results

According to [44], reducing input waveguide thickness improves the overall diffraction efficiency by reducing back reflection. This is shown in Figure 39 below. Back reflection is a function of grating $\Lambda_x$ and grating duty cycle. Therefore, the amount of reflection reduction is not uniform across the design parameter space. However as shown
in Figure 39, changing input waveguide thickness does not affect the shape of surface plot, it only changes its peak value. As a result, the following optimization strategy is followed: perform all optimizations using 250nm reduced thickness input waveguide. As the optimum design is located, using the design, and adjusting the first SWG duty cycle to look for the duty cycle that gives the most reflection reduction while reverting the input waveguide thickness to 500nm to compare which method gives the most reflection reduction.

![Figure 39](image)

Figure 39 [44] (a) Upward radiation with full thickness input waveguide (b) half-etched input waveguide

The optimization process for the directionality is straightforward as there are only three parameters in play: $ff_Y$, $\Lambda_x$ and $ff_{etch}$. For each $ff_{etch}$, a sweep of both $ff_Y$ and $\Lambda_x$ are performed to find the design point that gives the most $P_{upward}$ while monitoring the radiation angle of both TE and TM to make sure they are emitting towards the same angle.
Figure 40 $P_{\text{upward}}$ and radiation angle for both polarizations with 0.4 ffx$_{\text{etch}}$

Figure 41 $P_{\text{upward}}$ and radiation angle for both polarizations with 0.45 ffx$_{\text{etch}}$
Figure 42  $P_{\text{upward}}$ and radiation angle for both polarizations with 0.5 $fFx_{\text{etch}}$

Figure 43  $P_{\text{upward}}$ and radiation angle for both polarizations with 0.55 $fFx_{\text{etch}}$
Figure 40-43 show that at almost all points in the swept parameter space, both modes radiate toward the same angle. Two candidates with the best performance are selected and their corresponding geometric parameters are shown in Table 1. 3D simulations are performed to verify the results and to verify the angular beamwidth in terms of azimuthal and elevation angle. Far-field beam patterns of both candidates are shown in Figure 44 and performances are summarized in Table 2.

<table>
<thead>
<tr>
<th>Candidate 1</th>
<th>Candidate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 $ffx_{etch}$</td>
<td>0.5 $ffx_{etch}$</td>
</tr>
<tr>
<td>0.6 $ffy$</td>
<td>0.65 $ffy$</td>
</tr>
<tr>
<td>0.62405 $ffx$</td>
<td>0.6071 $ffx$</td>
</tr>
<tr>
<td>643nm $\Lambda_x$</td>
<td>643nm $\Lambda_x$</td>
</tr>
</tbody>
</table>

Table 1 Optimized geometrical parameters of both candidates

![Figure 44 Far-field radiation pattern for both candidates](image)
<table>
<thead>
<tr>
<th></th>
<th>Can_1 TE</th>
<th>Can_1 TM</th>
<th>Can_2 TE</th>
<th>Can_2 TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{upward}} )</td>
<td>55%</td>
<td>62.8%</td>
<td>57.19%</td>
<td>58.96%</td>
</tr>
<tr>
<td>( P_{\text{downward}} )</td>
<td>27.9%</td>
<td>10%</td>
<td>20.1%</td>
<td>11.37%</td>
</tr>
<tr>
<td>( P_{\text{reflection}} )</td>
<td>5.9%</td>
<td>2.56%</td>
<td>5.83%</td>
<td>3.93%</td>
</tr>
<tr>
<td>( P_{\text{through}} )</td>
<td>11.22%</td>
<td>24.55%</td>
<td>16.87%</td>
<td>25.73%</td>
</tr>
<tr>
<td>Radiation angle (( \theta ))</td>
<td>13.67</td>
<td>13.67</td>
<td>14.18</td>
<td>13.67</td>
</tr>
<tr>
<td>Beamwidth (( \theta \times \varphi ))</td>
<td>12.38 x 85.62</td>
<td>11.86 x 83.55</td>
<td>12.38 x 83.55</td>
<td>12.38 x 85.62</td>
</tr>
</tbody>
</table>

*Table 2 Performance metrics of both candidates*

\( P_{\text{reflection}} \) and \( P_{\text{through}} \) are similar to \( P_{\text{upward}} \) and defined in equation 3.10 and 3.11.

Beamwidth is characterized as the full width half maximum (FWHM) angular range of the main lobe in both \( \theta \) and \( \varphi \) angle. This is done by taking a 2D cut in \( \theta \) and \( \varphi \) and extracting the FWHM from the plots as shown in Figure 45 using the far-field pattern of candidate 1 TE mode as an example.

\[
P_{\text{reflection}} = \frac{\text{power reflected into the input waveguide}}{\text{total input power}} \quad (3.10)
\]

\[
P_{\text{through}} = \frac{\text{power remained in the output waveguide}}{\text{total input power}} \quad (3.11)
\]
Results in Table 2 show that both candidates have close to 60% $P_{\text{upward}}$ for both TE and TM polarizations and similar beamwidth in both polar angles.

**Reflection optimization**

Reduced input waveguide thickness shows lower than 6% reflection for both designs. As mentioned above, a different method in reducing $P_{\text{reflection}}$ will be implemented and to compare with the above results in Table 2. Given the similarity in performances between two candidates, candidate 1 is selected to perform further simulations and optimizations on. Figure 46 illustrates the simulations that are performed to see how changing the duty cycle of the first SWG element ($ff_{\text{first}}$) would affect $P_{\text{reflection}}$. 

*Figure 45 (a) elevation cut and (b) azimuthal cut of the far-field radiation pattern*
Figure 46 Antenna with $ffy_{first}$ equals (a) 0.3, (b) 0.5. Sideview of the antenna with (c) 500nm thick input waveguide and (d) 250nm thick input waveguide

First, 3D simulations that scan $ffy_{first}$ are performed using both 500nm and 250nm thick input waveguide as illustrated in Figure 46 (c) and (d). The scanning range of the $ffy_{first}$ has been limited to between 0.35 and 0.65 due to the 100nm feature size design rule. $P_{\text{reflection}}$ vs $ffy_{first}$ plots for both TE and TM polarizations are drawn in Figure 47, which are obtained through 3D FDTD simulations. The results in Figure 47 show that 250nm thick input waveguide offer lower reflection compared to 500nm thick input waveguide at all $ffy_{first}$ values. This difference in performance is more significant in TE mode as the plots show on average more than 20% reduction in reflection across all $ffy_{first}$. The plots also show that $P_{\text{reflection}}$ drops as $ffy_{first}$ becomes larger. At $ffy_{first}$ of 0.65, $P_{\text{reflection}}$ are 3.99% and 2.55% for TE and TM mode respectively compared to 5.9% and 2.56% at $ffy_{first}$ of 0.6.
Although $ffy_{\text{first}}$ of 0.65 provides lower reflection, it has a smallest feature size of 105nm vs 120nm that $ffy_{\text{first}}$ of 0.6 would otherwise has. Therefore, $ffy_{\text{first}}$ of 0.6 remains to be the best design so far.

**Figure 47** $P_{\text{reflection}}$ as fill factor of the first SWG section changes for (a) TE mode (b) TM mode

**Upper cladding thickness optimization**

Like BOX, upper cladding (top oxide, TOX) can also form a cavity as demonstrated in [50]. This means that the thickness of the TOX ($t_{\text{TOX}}$) also affects the amount of upward radiation the antenna can provide ($P_{\text{upward}}$). Therefore, using the optimum design found from previous steps, a scan of $t_{\text{TOX}}$ is performed for both polarizations and the results are shown in Figure 48. Despite using a less accurate 2D simulation as shown in Figure 48 (a), a periodic fluctuation of $P_{\text{upward}}$ as $t_{\text{TOX}}$ changes is clearly shown, which has indicated cavity effect formed by the upper cladding. A more accurate 3D simulation sweeping $t_{\text{TOX}}$ between 2.15\(\mu\text{m}\) and 2.3\(\mu\text{m}\) is then performed, and the result is shown in Figure 48 (b). A shift in peak performance is observed between the 2D and 3D simulation. Considering a
balance between the performance of TE and TM mode, a $t_{\text{TOX}}$ of 2.2$\mu$m is chosen, which coincidently is the value that has been used throughout all the simulations and optimizations.

![Figure 48](image)

$P_{\text{upward}}$ vs upper cladding thickness in (a) 2D FDTD simulation and (b) 3D FDTD simulation

$P_{\text{upward}}$ increases as the width and length of the antenna increases given the number of diffracting element increases. Therefore, it is possible to maximize the $P_{\text{upward}}$ by having a large enough antenna. An optical antenna can be treated as a diffraction grating with multiple slits and each period of the antenna is equivalent to a slit of a diffraction grating. However, the resolving power of grating, which is defined as the angular width of the principal fringe, in our case, the angular beamwidth of the antenna far-field pattern, is inversely proportional to the number of diffraction element according to [51]. The angular beamwidth of an antenna (element factor) should be maximized according to equation 2.4 because a larger element factor means larger steering range of an OPA system. As a result, it is necessary to make a balance between the $P_{\text{upward}}$ and beamwidth of the antenna by choosing the proper antenna dimension. First, a sweep of the number of periods along the propagation direction is performed to evaluate its corresponding $P_{\text{upward}}$ and beamwidth $\theta$. The results shown in Figure 49 clearly illustrated the relationship between beamwidth and
number of periods stated in [51]. Benchmarking against other published results [34], [36], [52], 10 period along the propagation direction is chosen, which gives beamwidth $\theta$ of 12.89° and 11.86° for TE and TM polarization respectively while retaining high $P_{\text{upward}}$.

![Graphs showing $P_{\text{upward}}$ and beamwidth $\theta$ vs number of period in length ($N_x$)](image)

**Figure 49** $P_{\text{upward}}$ and beamwidth $\theta$ vs number of period in length ($N_x$)

Similar to number of periods along the length, the width of the antenna, which is determined by the number of SWG period ($N_y$), also affects the $P_{\text{upward}}$ and the far-field pattern beamwidth. A simulation scan of $N_y$ is performed, and the results are shown in Figure 50. Figure 50 (a) shows that for TE mode, $P_{\text{upward}}$ stays almost unchanged once $N_y$ is larger than 9. Although $P_{\text{upward}}$ for TM mode still increases as $N_y$ is greater than 9, the rate of increase becomes smaller. Figure 50 (b) reveals that as $N_y$ increases, azimuthal beamwidth $\phi$ decreases while $\theta$ remains almost unchanged (simulation resolution is responsible for the small fluctuation of $\theta$ beamwidth shown in Figure 50 (b)). This observation aligns with the theory mentioned in [51]. In general, the dimension of the antenna is inversely proportional to the antenna far-field pattern beamwidth. The dimension of the antenna in x or y axis (number of diffracting elements in each axis) each decides one of the two angular beamwidths of the far-field radiation pattern. Specifically,
the length and width of the antenna are inversely proportional to the beamwidth in $\theta$ and $\phi$ respectively. Given that the goal is to maximize the $P_{\text{upward}}$ while maintaining the highest possible beamwidth in both $\theta$ and $\phi$, 9 period in $y$ ($N_y = 9$) is chosen as the optimum design, which has $P_{\text{upward}}$ of 53.7% and 60.6% for TE and TM respectively. A bandwidth analysis is also conducted as shown in Figure 51.

![Figure 50](image1.png)  
**Figure 50** (a) $P_{\text{upward}}$ (b) Beamwidth vs number period in width ($N_y$)

![Figure 51](image2.png)  
**Figure 51** Bandwidth analysis of the final design operating under (a) TE mode (b) TM mode

3.6 Input stage design and optimization

Throughout the optimization of the proposed antenna, the input waveguide has been assumed to be a buried ridge waveguide that is $2.88\mu m$ in width and $250\text{nm}$ in thickness.
as shown in Figure 46 in order to launch both the ideal TE and TM modes into the antenna. However, in practice, a ridge waveguide this wide is rarely used for the purpose of preventing propagation of higher-order modes. For instance, a 0.3μm high waveguide should not be wider than 0.35μm to achieve single-mode condition [53]. On the other hand, silicon-based rib waveguide supports single-mode operation for a large range of waveguide sizes [54]. Therefore, a rib waveguide-based inverse taper is proposed to use as the input stage of the antenna, which is illustrated in Figure 52. Similar input stage designed for grating coupler has been reported in [47]. On the left, a single-mode rib waveguide is used to interface with the rest of the optical I/O and at this point, modes of both polarizations are confined in the rib part of the waveguide. The inverse taper has a rib width that is gradually decreasing along the propagation direction which forces the modes into the slab region. The mode field profiles at both ends of the inverse taper is shown in Figure 52.

![Illustration of antenna with input stage and mode profiles of rib waveguide](image)

The design parameters of the inverse taper are shown in Figure 53, which are `initial_rib_width`, `final_rib_width` and `taper_length`. The width of the bottom slab is the
same width as the optimized antenna, which is 2.88µm. The etch depth is kept at 250nm to avoid additional etching step on top of what is already needed to fabricate the antenna itself.

![Figure 53 Inverse taper (a) (b) side views with upper cladding removed and (c) top view with slab removed](image)

The first step is to design the start of the inverse taper so that it supports the propagation of fundamental TE and TM modes only. According to [55], the range of initial_rib_width that would satisfy the single-mode condition can be obtained by plotting the effective indices of the modes vs initial_rib_width. The single-mode range is within which that both fundamental TE and TM modes’ effective indices are higher than rest of modes and at the same time, higher than that of the slab TE mode. Such plot is shown and the optimum range of initial_rib_width is labelled in Figure 54. The plot shows a rib width between approximately 420nm and 720nm results in a single-mode rib waveguide. Therefore, an initial_rib_width value of 700nm is selected to perform further optimization.
Next step is to properly design the end of the inverse taper, so that both TE and TM modes are pushed downward into the slab and at the same time, have the best overlap with the ideal modes that would otherwise be generated by the 250nm-thick buried ridge waveguide. The ideal fundamental TE and TM modes field profiles are plotted in Figure 55 and these are the modes that the modes at the end of the inverse taper should match. A scan of rib width shows how well the modes supported by the rib overlaps with the ideal modes and the results are shown in Figure 56. As expected, the results show that for both polarizations, the smaller the rib is, the more overlap there is with the ideal field excitations. Clearly, a 50nm rib gives good overlaps with both polarizations. However, it would require more advanced fabrication technique such as e-beam lithography. Both 50nm and 100nm are selected to perform the final taper_length scan.
The final taper length is performed to find the optimum length of the taper and the result is shown in Figure 57. TE0-TE0 power transfer shows a smooth increase as the taper length is increasing in both plots. This is expected given that the longer taper means a less abrupt change of geometry which facilitates a better mode power transfer. However, in the case of TM0-TM0, the power transfer into the TM0 mode caps at a certain taper length and almost linearly decreases after that. This phenomenon is referred as “mode hybridization” in [56], where the fundamental TM mode propagates in a vertically asymmetric waveguide experiences power transfer into odd number TE mode such as TE1, TE3 and TE5 etc. Rib waveguide is a vertically asymmetric waveguide by nature and therefore is affected. This can be confirmed by plotting the power coupled into other modes by running mode
expansion simulation and the result is shown in Figure 58. As the inverse taper becomes longer, power starts coupling into higher order TE modes. Based on the simulations, for a taper with \texttt{final\_rib\_width} of 50nm, a taper length of 11.8\(\mu\)m is chosen which achieves a power transfer of 92\% and 80\% for fundamental TE and TM modes respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure57.png}
\caption{Mode power transfer vs taper length for (a) 50nm-wide taper tip and (b) 100nm-wide taper tip}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure58.png}
\caption{Mode hybridization for (a) 50nm-wide taper tip and (b) 100nm-wide taper tip}
\end{figure}

3.7 Losses

According to [57], typical losses in silicon waveguide come from sidewall roughness, absorption, and material loss. Sidewall roughness losses are scattering loss due to imperfection in waveguide fabrication. Such loss could be seen in the form of increased radiation loss or reflection loss. Atomic force microscope can be used to quantify the level of sidewall roughness. Throughout our design, the sidewall roughness is neglected in our
simulation modelling. Absorption loss in silicon is wavelength-dependent. The reference wavelength in our design is 1550 nm, which is above the band edge wavelength of silicon. Therefore, absorption loss is negligible in this case. Lastly, material loss is due to impurities in material, which is often taken into account in a doped material. Since optical antennas are passive devices, the material loss does not need to be considered. The main sources of losses considered in our analyses come from three sources: reflection at the interface of the input taper and the grating structure, downward radiation into the substrate, and undiffracted power. We acknowledge that fabrication related issues from sidewall roughness and dimensional variations will have a significant impact to our designs. Special considerations for accommodation in geometry dimensions should be taken in account when prototype devices are fabricated for experimental demonstration.

3.8 Conclusion

A compact polarization-insensitive optical antenna based on 500nm silicon film has been designed that is able to emit both fundamental TE and fundamental TM mode to $13.67^\circ$ from vertical upright direction. It has a compact footprint of 6.43$\mu$m x 2.88$\mu$m in length and width respectively. Despite its compact footprint, it radiates over 50% of the input power to upward radiation for both polarizations thanks to the L-shaped diffracting elements. The input waveguide has been carefully designed to minimize back reflection. A low reflection of only 5.9% and 2.56% for TE and TM mode respectively is achieved. The designed antenna uses subwavelength metamaterial for polarization control and the minimum feature size is 120nm, which meets the minimum feature size requirement for fabrication. The device is also designed to achieve best performance with 3$\mu$m buried oxide
(BOX) layer and 2.2\(\mu\)m top oxide (TOX) layer, which are the thicknesses that are commercially available in silicon photonics foundries. Finally, the antenna achieves a FWHM far-field beamwidth \((\theta \times \phi)\) of 11.86° x 106.25° and 11.86° x 104.18° centered at its designed radiation angle 13.67° for TE and TM mode respectively.

A single-mode inverse taper based on SOI rib waveguide is also designed to be used as the input stage of the antenna. The 11.8\(\mu\)m-long inverse taper starts with an initial_rib_width of 700nm and ends with a final_rib_width of 50nm. The designed inverse taper has a power coupling efficiency of 92% and 80% for TE0 and TM0 modes respectively. At the end of the taper, modes are confined in the bottom slab only and therefore serves as the ideal input into the designed antenna.
Chapter 4 Experimental characterization setup design for an OPA

An OPA imaging system is designed for testing on-chip OPAs. In this work, we use a prototype OPA chip fabricated by Honeywell, our industry partner. The prototype OPA chip allows us to ensure the setup is properly designed and provides the anticipated characterization functions. The setup is designed to observe and characterize both the OPA’s near-field and far-field radiation pattern. The setup is needed to confirm whether a constructive interference of all emitters is happening at far-field. The near-field observation is to confirm if all emitters are functioning properly by making sure each are emitting light.

4.1 Far-field imaging basics

Far-field radiation refers to the radiation pattern formed at some distance from the antenna. Because of the distance, the wavefront of the interfered waves between antenna become very flat such that in a ray tracing diagram, the input ray can be regarded as parallel rays (plane wavefront). In contrast, the near-field refer to the radiation pattern very close to the emitting antenna, typically shorter than one wavelength. This results in a non-flat but rather diverging wavefront. Therefore, the near-field is modelled as a diverging input ray in a ray tracing diagram. By using combinations of lenses, these rays are magnified and projected onto a camera sensor. Using similar concepts, optical far-field imaging setup has been demonstrated [15], [34], [58]–[61]. Such setup typically includes a detachable near-field imaging section so that the near-field and far-field can be observed by simply removing or inserting a lens. An illustrative ray tracing diagram is presented in Figure 59. Figure 59 (a) shows the imaging principle of far-field. Yellow and blue rays represent parallel rays coming from different angle, which simulates the steering of the OPA far-
field beam. Lens 1 projects parallel rays onto its back focal plane with a lateral spatial offset. Lens 2 and lens 3 reproject the rays onto the camera sensor with some level of magnification. Figure 59 (b) shows the working principle of the near-field imaging. In this illustrative diagram, three lenses are used to image the far-field and two are used for the near-field imaging. In practice, these number vary. For example, [59] uses two lens to project the far-field onto camera sensor while [60] uses four lenses to image the near-field. Regardless the number of lenses used, the principle remains unchanged, which is projecting either parallel or diverging rays onto the camera sensor with a suitable magnification.

4.2 OPA under testing

As with all on-chip OPAs demonstrated so far, the Honeywell’s OPA consists of several essential passive and active optical components such as an edge coupler, beam splitters, phase shifters, routing waveguides and grating antennas. A layout of the fabricated on-chip OPA is shown in Figure 60. Key components of the main OPA system are labelled, while other devices on the layout are test structures for characterization purposes. A zoomed in view of the main array is shown in Figure 61. The array has a dual-ring geometry consists of 100 identical antennas in total. Each antenna is accessed by a single waveguide. A tapered fiber is used to inject light onto the OPA through the edge
coupler. This single input waveguide then splits into 100 optical paths by layers of MMI beamsplitters. One thermal optical phase shifter is placed on top of each waveguide to tune the phase of each waveguide mode by changing the temperature of the waveguide.

Figure 60 Honeywell OPA layout
4.3 Simulation Tools

4.3.1 MATLAB Phased Array Toolbox

The MATLAB phased Array Toolbox [62] is an add-on package provided by MATLAB to simulate the response of phased array system given the geometry of the array, emission pattern of antenna and operating wavelength. The tool is used to create a phased array far-field simulator, which is used to generate simulated far-field radiation patterns shown in Figure 62. Given a few broken antennas on the fabricated OPA chip, the simulator is useful in determining whether the OPA can still phase up despite the broken antennas. Also, it helps to determine the accuracy of the imaging setup by comparing the images taken by the setup and the simulated images.
4.3.2 ZEMAX OpticStudio

ZEMAX OpticStudio [63] is a ray-tracing software made by ZEMAX. It models the free space optical path of the light after going through various optics. As an import part of OPA testing, visualization of far-field is necessary to characterize system performance such as beam quality and beam steerability. OpticStudio is used to model the ray-tracing of OPA beam to ensure that the far-field pattern can successfully form at the camera sensor plane by using appropriate combination of optics. The distance between each optics must also be accurately modeled using ZEMAX. All ray tracing diagrams in section 4.5 are created using ZEMAX.

4.4 Design targets

The optical setup is designed to observe both the near-field and the far-field of the light emitted by the array. The OPA uses 1550nm operating wavelength therefore all the ray tracing modelling that observes the light from the OPA needs to use 1550nm wavelength. Besides, the setup is also designed to observe the chip visually using a regular visible camera. This ensures that the edging coupling process is smooth very time the tapered fiber is coupled into the chip so to prevent damage to the chip. This part of the ray tracing simulation is done using visible wavelength. Therefore, three ray tracing simulations need to be completed and the requirement for each needs to be fulfilled simultaneously on the same setup. According to Huygens principle, light is formed by individual element called wavelet. Each wavelet is emitting light towards all directions and the wavelet is at the source of that sphere, therefore at a distance close to the object, the waves are still diverging, and the wavefront is spherical. As the spherical wavefront
propagates for a certain distance and reaches the far-field region, the radius of the sphere becomes larger, and the wavefront is considered flat for the same angular range. Therefore, at far-field region, we consider the resulting diffraction pattern to be a plane wave while that in the near-field region is a spherical wave. The following lists the design target and requirement for each.

**Far-field (IR)**

Given that all antennas on the array are in phase with each other and are producing a constructive wavefront, the far-field imaging setup should be expected to capture the full designed steering range of the OPA, in our case, is $+20^\circ$ to $-20^\circ$. As mentioned above, the far-field is modelled as parallel incoming rays given the flat wavefront as shown in Figure 59 (a). The width of the ray is set to be 0.6μm, which is roughly the size of the array. This sets out several requirements that the imaging setup needs to meet. First, all lenses especially the first lens need to be large enough to capture all the parallel rays that is within the $+20^\circ$ to $-20^\circ$ steering range. This should also hold true throughout the ray tracing until the final focused rays hit the camera sensor.

While performing the far-field ray tracing design, it should also be noted that the pixel usage on the camera sensor should be maximized. The IR camera used in the experiment is a Xenics Bobcat 640 camera, which has a pixel size of 640 x 512. The sensor active area dimension is 12.8mm x 10.24mm.

**Near-field (IR)**
The purpose of observing the near-field emitted from each antenna is to ensuring successful coupling of laser into the chip as well as examining for any non-emitting antennas. Such non-emitting could be caused by various factors such as broken waveguide, antenna fabrication error, etc. Due to the large number antenna integrated on the OPA, several non-functioning antennas would still result in very similar far-field image compared to an array with all antennas working properly. A comparison between two far-field images can be found in Figure 62. The insets represent the geometry of the arrays that were used for the simulations, which correspond to the actual array layout shown in Figure 61. Figure 62 (b) simulates the array with 17 non-emitting antennas, which is the actual number of broken antennas of the OPA observed under the near-field imaging setup as shown later in Figure 70. Two images are very similar. By merely looking at array’s far-field, it is difficult to quantify the number of working antennas and is even almost impossible to identify which ones are broken. Therefore, the near-field observation is necessary. Magnification level is the only thing that needs to be considered during the design of the imaging setup. Considering the size of the array of 0.6µm and camera sensor active area of 12.8mm x 10.24mm, a magnification level of around 5 is targeted. This is done by choosing the appropriate combination of lenses with suitable effective focal length (EFL).
Near-field (Visible)

The concept for visually observing the surface of the chip is very similar to the near-field IR observation. Moticam 3+ USB microscope camera is used in the setup. The camera uses a half inch sensor. A magnification of 3 is chosen as the target design as a 1.8mm image projected onto the sensor gives a detailed image of the chip edge for edge coupling using tapered fiber.

Because both IR and visible cameras are implemented on the same setup, a beam splitter that separates corresponding wavelength into each arm is required. In our setup, a dichroic mirror that splits the NIR wavelength from visible wavelength is used. A diagram which shows the proposed setup is shown in Figure 63. As seen, the NIR wavelength, which is the light emitted from the OPA, should stay uninterrupted going through the dichroic mirror and reach the IR camera while the visible wavelength is reflected into the horizontally mounted arm and reaches the visual camera eventually.
4.5 Choice of optics

As shown in Figure 59 and Figure 63, an ideal lens should either have the best collimating or focusing ability depending on where the lens is placed in the optical path. Figure 64 shows ray tracing simulations of some of the commonly available lenses, namely aspherical lens, achromatic doublet lens and spherical singlet lens. The simulation shows that aspherical lens focuses the collimated input best compared to the other two types of lenses. Since the far-field imaging quality is the priority, lens 1 and lens 3 in Figure 59 will use aspherical lenses.
Lens 2 is used in both the far-field imaging and the near-field imaging, which means that they are required to perform both focusing and collimation. Ideally, an aspherical lens can be used with a flipping mechanism. The plano side of the aspherical lens faces the diverging input while collimating the light and the curved side faces the collimated input while focusing the light as shown in Figure 65. However, mechanically implementing the flipping in the setup can easily introduce optical misalignment. Therefore, an analysis on a single lens’ ability to both focus and collimate without flipping is performed. The simulations are shown in Figure 66. The simulation shows that for lens 2 to have the best far-field imaging quality (collimating), an inversely placed aspheric lens should be used. However, it performs poorly when focusing and the result of it would be a blurry image when imaging the near-field of the OPA. In comparison, an aspheric lens with opposite orientation (Figure 66-b) and an achromatic doublet (Figure 66-c) both perform similarly well for both collimating and focusing although as expected neither of them can create
perfectly collimated light. Given the lenses’ available choices for focal length and the cost consideration, achromatic doublet is used for lens 2.

Figure 65 Flip the lens to focus and collimate respectively

Figure 66 Simulated collimation and focusing of (a) flipped asphere (b) asphere (c) achromatic doublet
Figure 66 (b) shows the working scenarios of lens 1 under the near-field (collimating) and the far-field (focusing) imaging respectively. It is expected that the near-field image quality is slightly blurry due to lens 1’s inability to produce perfectly collimated light on top of imperfect focusing on lens 2. This is a compromise of achieving the best far-field imaging on the same optical setup without flipping the lenses. Figure 67 (a) shows the simulated ray trace of the full far-field imaging setup. The simulation models three different ray traces with $+20^\circ$, $0^\circ$ and $-20^\circ$ beam steering respectively. The ray trace shows that the far-field diffraction for this steering range is projected onto the camera sensor with tight focus. This indicates the far-field (fourier plane) is well imaged on the sensor plane. Figure 67 (b) shows a zoomed in view of the projection and a total 5.4mm of sensor active area is used. This is a decent portion of the camera sensor given the sensor size is 12.8mm x 10.24mm. This sensor area usage is mainly limited by the usage of small lens.

Prior to imaging the far-field of the real OPA chip, the far-field imaging setup is experimentally aligned and tested by using a fiber collimator with a steering mount. Specifically, the steering range of the setup is tested to make sure the setup is indeed achieving a $40^\circ$ field of view. The $+20^\circ$ to $-20^\circ$ of steering is well observed on the IR camera as shown in Figure 68. As predicted, the $40^\circ$ of total steering range occupies about half of the camera sensor. This is an indication that the far-field imaging setup is behaving as designed.
The ray trace of the near-field imaging is also simulated, and the result is shown in Figure 69. Figure 69 (a-1) and (b-1) show the ideal (flip lens 1) and practical case when imaging the near-field. As expected, because the aspherical lens can only achieve the best collimation when the plano side faces the object, (b-2) shows a significant amount of defocus at the sensor plane compared to (a-2), which the near-field in turn is well imaged onto the camera sensor. Both cases are also experimentally tested, and the result is shown in Figure 70. Figure 70(a) shows the near-field imaging corresponding to scenario in Figure 69 (a-1). Light is well coupled into the emitters of the array except several non-functioning
emitters which are potentially caused by broken waveguide. The geometry of the array is well observed, and each emitter can be clearly identified. The working condition of individual emitter can be confirmed as some emitters are not lit up, which has indicated possibly a broken waveguide. In contrast, a blurry image of the same array is shown in Figure 70(b), which corresponds to the ray trace of Figure 69(b-1). A significant amount of defocus is observed as expected. The general shape of the array can be recognized, and the coupling can be confirmed, however the working condition of individual emitter cannot be identified.

*Figure 69 near-field imaging ray tracing for (a-1) ideal setup, (b-1) practical setup and their corresponding zoomed in view at the sensor (a-2) and (b-2) respectively*
The ray traces for the visual branch under both lens orientations are also simulated and are presented in Figure 71. The visual branch is created after lens 1 as illustrated in Figure 63 by using a dichroic mirror beam splitter. The two lenses in Figure 71 then correspond to the lens 1 and lens 4 in Figure 63. A 100mm focal length achromatic doublet with anti-reflection (AR) coating in the visible wavelength range is used as lens 4. The result draws similar conclusion as Figure 69 does: aspheric lens does not collimate beam well when the curved side is facing the object and therefore create a defocused image at the sensor. The imaging setup in the visible branch is experimentally tested and sample pictures are shown in Figure 72 under both orientations for lens 1. Figure 72 shows pictures at two different locations on the chip: edge coupler section and array section. It can be clearly seen that when the plano side of lens 1 is facing the object, the images are sharper, and more details can be resolved. Figure 72 (a) and (b) show the difference in the imaging quality on the tapered fiber and the edge of the chip; (d) shows not only the dual-ring array geometry but also the waveguides leading to the emitters while (b) only the array geometry is identifiable. This result match the ray traces simulated in Figure 71.
Figure 71 Ray traces of the visual branch when (a) curved side of lens 1 faces the object (not flipped) (b) plano side of lens 1 faces the object (flipped)

Figure 72 Near-field images on the edge coupler and array under visible wavelength for different lens 1 orientations

From the above ray tracing simulations and the experimental observations, it can be concluded that flipping lens 1 indeed lead to a much better image quality for imaging the near-field in both IR and visible wavelength. However, the purpose of the imaging the
near-field is to first, make sure the tapered fiber tip is at a safe distance away from the edge of the chip to prevent potential damage and second, to make sure the coupling is successful by observing the light emitted from the array in IR. As the results shown in Figure 70 and Figure 72, both requirements can be fulfilled without flipping lens 1, although with noticeable lower imaging quality. Given that lens 1 must remained un-flipped to image far-field and the flipping itself can affect optical alignment as well as potentially damaging the chip under test since the vertical setup, it is concluded that lens 1 remains the same orientation for imaging both the near-field and the far-field. An assembled imaging setup is shown in Figure 73.

![Figure 73 Assembled OPA imaging setup](image)
Finally, the far-field images are taken, and the result is shown in Figure 74 (a). The random speckle pattern is expected given that each emitter emits light with random phase errors (array not phased up). Figure 74 (b) is the simulated far-field radiation pattern of the OPA under testing (with 17 antennas broken). It is obtained by taking the top view of Figure 62 (b) and then discretizes the intensity level to mimic the actual images taken by the IR camera. Comparing the two images, despite the brighter background in Figure 74 (a) which could be due to the static background stray light on the surface of the chip, the speckled pattern is noticeable. Under experiment, noticeable fluctuation of radiation pattern (due to interferences) is noticed while modulating the phases of the antennas with sinusoidal signals. Although the real image does not look very similar to the simulated image, which could be caused by uneven power distribution between antennas due to fabrication, slight shifting of antenna from optimum location and slight defocus at the sensor plane for off-axis beam compared to on-axis beam as shown in Figure 67 (b). However, as long as the speckled pattern is noticeable and the interferences are observed while modulating the phases of antennas, it could be confident to say that the far-field imaging setup is working as intended. [64]

Figure 74 (a) Observed far-field with random phase errors (b) simulated far-field radiation pattern
Chapter 5 Conclusion and future work

The two projects covered in this thesis are both related to OPA. The first is the design of optical antenna that operates under both fundamental TE and TM polarizations for enhanced bandwidth. The second is the design and measurement of a far-field imaging setup that is used to observe the far-field radiation pattern of an OPA on chip.

The polarization-insensitive antenna proposed in this thesis is based on 500nm-thick silicon film. The designed antenna is designed to allow injection of both fundamental TE and TM modes and emits both polarizations to the same angle. The antenna has a power diffraction efficiency of 53.7% and 60.6%, and beamwidth ($\theta \times \phi$) of $11.86^\circ \times 106.25^\circ$ and $11.86^\circ \times 104.18^\circ$ for TE and TM respectively. The main target of the work is to maximize the diffraction efficiency for both polarizations while keeping the footprint as compact as possible. As mentioned in Chapter 3, large beamwidth is also an important performance metric of an optical antenna as it directly relates to the steerability of a OPA system. A recently proposed optical antenna design in [65] achieved a very high beamwidth of $52^\circ \times 62^\circ$ and a diffraction efficiency of 82% for TE polarized input through near-field phase engineering. Similar idea can be explored in this work as well to further enhance the beamwidth of the antenna while maintaining the polarization-insensitive performance.

Besides designing the antenna itself, an optimized input stage is also proposed. The input stage is a single-mode inverse taper based a SOI rib waveguide that confines both polarizations in the slab region while exciting the antenna with the optimum modes. The inverse taper has a power coupling efficiency of 92% and 80% (equivalent to 0.36dB and 0.97dB) for TE and TM polarizations respectively. It is noted that the reason for lower TM coupling efficiency is the unintended power coupling into higher order TE modes, which
is referred to as “mode hybridization” in [56]. It also introduces techniques to potentially suppress the unintended mode transfer by using abrupt width change waveguide propagation. However, [56] explores the approaches for single polarization only on a normal taper, which makes the optimization a lot simpler. Although different, similar approaches might still be employed to suppress the TM mode hybridization in a dual-polarization setting.

Given the successful implementation of the far-field imaging setup, various tasks will be performed on the OPA under this setup. One of the most important tasks is trying to align the wavefronts (phases) of each antenna so that together they can produce a focused beam spot in the far-field. As Figure 74 (a) shows, random phases of the antennas result in a random speckled pattern at the far-field. Different techniques can be used to align the phases. Phase calibration using optimization-based methods [66], [67] or interference-based method [60] have been presented and similar technique can also be implemented on the OPA under testing using the designed far-field imaging setup. Following the alignment of the phase fronts, the steerability of the OPA can also be examined by changing the phases of individual antenna to create controlled phase offsets among individual antennas. These two projects have resulted the following two referred publications:

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- Daniel Benedikovic, Radovan Korcek, William Fraser, Carlos Alonso-Ramos, Laurent Vivien, Xiaochen Xin, Yousef Karimi Yonjali, Pavel Cheben, Jens H. Schmid, Maziyar Milanizadeh, Tom Smy, Ahmad Atieh, and Winnie N. Ye, Off-chip surface grating couplers and nano-antennas for optical communications and optical phased arrays, Photonics North, Montreal, June 12th, 2023
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