Polarization Control for Silicon Photonic Circuits

by

Jan Niklas Caspers

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Graduate Department of Electrical and Computer Engineering
University of Toronto
2014

In recent years, the field of silicon photonics has received much interest from researchers and companies across the world. The idea is to use photons to transmit information on a computer chip in order to increase computational speed while decreasing the power required for computation. To allow for communication between the chip and other components, such as the computer memory, these silicon photonics circuits need to be interfaced with optical fiber.

Unfortunately, in order to interface an optical fiber with an integrated photonics circuit two major challenges need to be overcome: a mode-size mismatch as well as a polarization mismatch. While the problem of mode-size has been well investigated, the polarization mismatch has yet to be addressed. In order to solve the polarization mismatch one needs to gain control over the polarization of the light in a waveguide.

In this thesis, I will present the components required to solve the polarization mismatch. Using a novel wave guiding structure, the hybrid plasmonic waveguide, an ultra-compact polarization rotator is designed, fabricated, and tested. The hybrid plasmonic rotator has a performance similar to purely dielectric rotators while being more than an order of magnitude smaller.

Additionally, a broadband hybrid plasmonic coupler is designed and measured. This coupler has a performance similar to dielectric couplers while having a footprint an order of magnitude smaller.

Finally, a system solution to the polarization mismatch is provided. The system, a polarization adapter, matches the incoming changing polarization from the fiber actively to
the correct one of the silicon photonics circuit. The polarization adapter is demonstrated experimentally to prove its operation. This proof is based on dielectric components, but the aforementioned hybrid plasmonic waveguide components would make the system more compact.
Acknowledgements

First, I would like to thank my supervisor, Prof. Mo Mojahedi for his support and guidance throughout the last years. Especially for taking me on when switching supervisors, for his willingness to trust me throughout the years, and for always giving me critical insight and making sure that my ideas are on solid ground with his questions.

Additionally, I would like to thank Prof. Aitchison, Prof. Janz, Prof. Helmy, Prof. Herman, and Prof. Qian for being on my thesis and defense committee and giving me critical feedback to help me improve my thesis to the best state possible.

Throughout the years, a large number of colleagues and staff have helped me with my work and I won’t be able to thank everyone in name, but I would like to specific gratitude to a selected few. Mainly, I would like to thank my group members, for helping me, proof-reading my thesis and papers, and making the last years a lot more enjoyable: Farshid Bahrami, Ahmed Dorrah, and Xiao Sun. Special thanks to Muhammad Alam for helping me with my first projects and for the successful collaboration on numerous hybrid plasmonic waveguides devices. Also, Arnab Dewanjee gets my special thanks for all the morning coffees, lots of insightful discussions, and for continuing my work.

During my PhD I also spent long hours in the cleanroom facilities of the former ECTI now, TNFC and I would like thank the technical staff that has helped me throughout the years. Especially, Alexander (Alex) Tsurkenik has given me a lot of insight into nanofabrication and was always there when needed, without his help I would still be years away from finishing my PhD!

Arash Joushaghani also deserves a lot of gratitude for helping me in the lab, giving me equipment, and mostly for always wanting to have a beer when the experiment just would not work and I needed to get away from it all for a few hours.

My family has supported my throughout the years and I am grateful for that, especially for supporting me to be away from them for the last years. They always make the world a happier and more interesting place.

Lastly, and most importantly I want to thank my wife Asya Caspers for always letting me bore her with my monologues about engineering, supporting me in all my endeavors and just for being herself. I am eternal grateful for having her in my life.
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Chapter 1

Introduction

In current times, information is usually processed using electrons in computer chips. Electrons were also the particles-of-choice to transmit information over vast distances using telegraph systems [1]. In the 1970s, these long range cables were slowly replaced by optical fibers [2]. Optical fibers allow for the efficient and economic transmission of significant amounts of information over long distances, thanks to the combination of low attenuation of signals in the fiber and easier regeneration of signal strength using erbium doped amplifiers [3]. Additionally, more than one signal can be sent down a single fiber using spectral multiplexing. As the amount of data transmitted between different places has been increasing continuously, shorter distance cables are replaced with optical fibers. The latest trend in industry is to replace Ethernet network cables in data centers with optical fibers [4]. These rack-to-rack optical connections occupy less space compared to electrical cables, while offering faster speeds and larger bandwidths.

The next step in optical communication will be optical connections between components in the computer, such as chip-to-memory or chip-to-chip connections [5]. Shortly thereafter, optical connections between the cores on a single computer chip. All these connections, when done optically, are commonly referred to as optical interconnects [6], will likely be introduced. Current computer chips are already limited in speed due to the bottleneck of information exchange between cores. This problem will only intensify in the near future, and thus large bandwidth, low power optical interconnects are a logical choice.

Intel is currently producing transistors on a computer chip using the 14 nm node [7], where node refers to the half-pitch between features. This means that typical features in a transistor, such as the gate width, are on the order of ten nanometer and will be shrinking further in the future. Typical photonic components such as waveguides, on the other hand, are at least 200 nm in width, and often even wider than 500 nm. Functional
components often occupy areas on the order of tens to hundreds of square micrometers. In summary, current thinking is that optics will not be used for information processing, as this can be done more efficiently and in a more compact manner using electrons. Optics will, however, serve to transmit information between the computation centers that use electrons for information processing.

Accordingly, in this thesis I will focus on how to transmit information using photonics, and not on how to process it using photonics.

1.1 Silicon Photonics

A number of materials have been proposed for optical on-chip interconnects, such as: InP or GaAs. In previous decades a lot of work has been done on these III/V systems and large progress has been achieved, especially in their application as integrated laser sources [8]. However in the last years silicon (Si) has also received a lot of attention due to a number of unique properties:

- The fabrication of silicon based devices is well established, thanks to billions of dollars of investment by the semiconductor industry.

- Silicon is transparent at a vacuum wavelength of 1.55 $\mu$m, the wavelength at which most optical fiber communication takes place, and thus low loss wave guiding is possible [9].

- Except for a light source, all components necessary (waveguides, modulators, detectors, multiplexer, etc.) for an optical link have been successfully demonstrated, and show at least comparable, if not better performance than their counterparts in other material systems [10].

- Most computer chips are made from silicon, thus silicon photonics could be monolithically integrated with MOSFETs to create an opto-electronic integrated circuit.

Given these advantages, it is not surprising that research in silicon photonics is already a few decades old. The earliest work was published in the 1980s, where Soref did much of this first work [11]. During the first decade, many components were still missing, such as high quality waveguides and modulators. Despite these shortcomings, the idea of photonics integration on the same substrate as electronics, and leveraging the silicon microelectronics infrastructure, were already prevalent. One of the earliest visions of an integrated opto-electronics circuit is shown in Fig. 1.1a).
In the 1990s, work started on building high quality silicon waveguides in order to route light efficiently [13]. Also, the problem of successful light integration into a silicon photonic chip began to emerge. Silicon is an indirect band-gap material, and thus a very inefficient light emitter. The band gap of silicon is also not compatible with the wavelength of choice for telecommunication. Silicon has a band gap energy that correspond to an optical wavelength of 1.2 μm, while most telecommunication applications are around a wavelength of 1.55 μm. First, work for light integration focused on using erbium doping, similar to the erbium doped amplifier for fibers [14]. Due to low efficiencies this idea was abandoned. Since then, a number of different approaches have been pursued, such as: noncrystalline silicon [15] or silicon raman lasers [16]. However, all these approaches had either low conversion efficiencies or required optical pumping, while electrical pumping is preferred. Currently the most likely solution is either an off-chip one, with light being coupled onto the chip using a fiber; or an III-V laser, which is either directly grown or bonded onto the silicon chip [17].

A more intense interest in silicon photonics began in the early 2000s, when commercial interest began to rise. Around this time the bottleneck of electrical interconnects and the rising power consumption of chips became a problem for the electronic industry. A good example of this change in the electronics industry is the Pentium IV, with its tremendous power consumption increase but small speed increase compared to the previous generation. After the Pentium IV, it became clear that newer computer chips would need to be faster without increasing the clock rate significantly [18]. Thus, Intel and IBM started to invest in photonics research. This interest cascaded and resulted in
a research in components, system approaches, fabrication and integration started. The final vision, however, has only changed a little between the 1980s and today. In Fig. 1.1 two visions for an optical chip can be compared. The left picture shows the early vision by Soref [11]; the right shows a recent vision by IBM. While there are artistic differences, the underlying vision has remained the same. Light is guided on top of the electronics chip, to allow communication between different components on the chip and also to communicate to components off the chip.

1.1.1 Waveguides

The first question that needed to be addressed in the design of an integrated optical was how to guide the light on the silicon chip. A waveguide is needed that allows for tight integration while having low optical loss with easy and reliable fabrication steps.

Initial waveguides were based on doping silicon or silica, similar to optical fibers [19]. The techniques for doping silicon were already well established, thanks to silicon electronics, thus making integration easy. However, the mode profile was large at $\sim 100 \mu m$ due to low confinement. The low confinement also sharply increased the required bending radii for low loss operation, thus preventing a compact integration. Additionally, optical attenuation was high due to free carrier absorption from the free carriers introduced by the dopant material.

An alternative to doped waveguides are rib waveguides. The guiding is achieved by partially etching a silicon slab. This silicon rib is surrounded with a low index material, such as silica. Rib waveguides have low loss and have typical mode profiles of a few microns. Electro-optical modulators [20], which take advantage of the plasma dispersion effect, [21] use rib waveguides. In electro-optical modulators the partially etched silicon slabs provide the electrical connection needed to drive the modulator in the rib regions.
Figure 1.3: A schematic snapshot in time of a surface plasmon polariton on a dielectric-metal interface. The arrows indicate the electric field. The closer to the interface, the stronger the field. The field couples to charge oscillations indicated by the + and − signs.

The current standard for routing light in a silicon photonics circuit are rectangular waveguides also called strip waveguides. A silicon strip with a typical height of 220 nm and a width of 450-500 nm forms the guiding layer and is surrounded by silica. The waveguides are fabricated by using a silica-on-insulator (SOI) substrate and fully etching the top silicon layer. Bends for the TE mode of the waveguide can be made as tight as 1 μm with a loss of less than 0.1 dB per bend. Propagation losses for large scale manufacturing are below 2 dB/cm [22]. A cross-section of the waveguide with superimposed mode profile for the TE mode is shown in Fig. 1.2.

1.2 Surface Plasmon Polaritons

Before continuing on the topic of photonics integration using silicon photonics, I want to introduce the subject of surface plasmon polaritons (SPP), which when utilized properly can reduce the size of optical components and devices. SPPs closely bind light to the surface of a metal, and they have opened new possibilities towards the realization of nanophotonic devices. Different devices, such as bio-sensors [23], waveguides, and interferometers [24] have been realized. The high field localization at the metal dielectric interface allows the confinement of light to spaces similar to the typical sizes of current transistors. Hence, SPPs combine a number of advantages from the fields of electronics and photonics.

The field concentration on the interface between the metal and dielectric is subwavelength, which explains the recent interest in SPPs. In this section, I will review some of the basic properties of SPPs. This section is mainly based on the paper by Barnes [25] and the book by Raether [26].
As stated earlier, SPPs are surface modes on a metal-dielectric interface (see Fig. 1.3 for a schematic representation). Free electrons on the metal surface collectively oscillate with the electromagnetic field. The electrons are accelerated by the electric field and oscillate on the surface. This changes the electric field, which again accelerates electrons, and so on. The electrons oscillate parallel to the direction of propagation of the SPP. This means that the oscillating component of the electric field also has to be parallel to the metal/dielectric interface. From this it is concluded that SPPs are a TM mode or $p$-polarized.

Much information can be inferred about the SPP from its dispersion relation: the relationship between the angular frequency $\omega$ and the wavevector $k_{SPP}$. For light in vacuum, the wavevector is given by $k_0 = 2\pi/\lambda_0$, or in terms of the angular frequency and energy by $k_0 = \omega/c = E/(\hbar c)$, where $\hbar$ is the reduced Planck constant. In a material the wavelength is reduced by the refractive index, leading to an increase in momentum $k = n k_0 = \sqrt{\epsilon} k_0$. Since a SPP has fields both in the dielectric and the metal, the dispersion relation depends on the dielectric function of both materials.

For the exact dependency of the dispersion relation one has to solve Maxwell equations to obtain

$$k_{SPP} = \frac{\omega}{c_0} \sqrt{\frac{\epsilon_d + \epsilon_m}{\epsilon_m + \epsilon_d}},$$  \hspace{1cm} (1.1)

where $\epsilon_{m,d}$ are the dielectric functions of the metal and dielectric, respectively.

Since the dielectric function of a metal (here gold) is complex, the SPP wave vector is also complex, with the real part of the wave vector describing the dispersion relation. For small wave vectors, corresponding to long wavelengths, the light line and the SPP line are very close together, while for shorter wavelengths (larger wave vectors) the SPP dispersion is below the light line. This gap between the SPP dispersion and the light line is the momentum mismatch, which means that to couple energy between the light and a SPP one has to somehow increase the in-plane momentum of the light. The mismatch also ensures that the SPP is bound to the surface, since it requires a mechanism to account for the additional momentum if the SPP is to radiate.

The SPP is a propagating coupled field-electron oscillation, thus, it also has a wavelength associated with it, which is calculated by taking the real part of Eq. (1.1)

$$\lambda_{SPP} = \lambda_0 \Re \left[ \sqrt{\frac{\epsilon_d + \epsilon_m}{\epsilon_m \epsilon_d}} \right] = \Re \left[ \frac{2\pi}{k_{SPP}} \right],$$  \hspace{1cm} (1.2)

The imaginary part of the dispersion relation describes the propagation length. A substantial part of the electric field for a SPP is concentrated in the metal, where the
Figure 1.4: The propagation length of a SPP is plotted for different gold/dielectric combinations as a function of vacuum wavelength. The length is defined as the distance after which only \(1/e\) of the SPP energy remains.

SPP energy is converted into heat. This conversion limits the propagation length of the SPP to the range from microns to millimeters. In Fig. 1.4 the distance when only \(1/e\) of the energy remains is shown. Similar to the skin depth in a metal, this distance \(\delta_{SPP}\) is found by examining the imaginary part of the \(k\)-vector:

\[
\delta_{SPP} = \frac{1}{2\Im\left[ k_{SPP} \right]} = \frac{\lambda_0}{2\Im\left[ \sqrt{\frac{\epsilon_d + \epsilon_m}{\epsilon_m\epsilon_d}} \right]}.
\] (1.3)

The factor of \(1/2\) appears because the propagation length is defined for the energy and not the electric field.

As seen in Fig. 1.4, the SPP propagates for shorter distances if the dielectric constant of the dielectric layer is larger. This is due to a larger field amplitude at the interface, which grows as the dielectric constant of the dielectric overlayer increases. Due to the energy conservation, this leads to more field concentration in the metal; thus, more of the SPP energy gets absorbed.

The tight field concentration allows for small plasmonics components, while the short propagation distances limit the use for communications applications as most light will be absorbed before reaching the next components. Different waveguide designs have been developed to overcome this limitation; however, the majority of these designs trade larger mode sizes for longer propagation lengths (e.g. long range surface plasmon polaritons [27]). Other designs allow for very small mode sizes, but limit the propagation length significantly (e.g. metal-insulator-metal waveguides [28]). One alternative to this trade-off, the hybrid plasmonic waveguide, will be discussed in Chapter 2.
Chapter 1. Introduction

Figure 1.5: The change of the polarization state in an optical fiber due to applied stress [31].

1.3 Polarization Control

Silicon photonics and SPPs allow for larger bandwidth optical communication on chip, but need to be interfaced with optical fibers to transport information on/off the chip [29]. The polarization in an optical fiber can change due to induced stress or temperature changes, and light can be transferred between the two orthogonal polarization components (as visible in Fig. 1.5). On the other hand, silicon waveguides can be designed to have both polarizations present (TE & TM), but their mode properties, such as effective index, mode confinement and others, will be different for the two polarizations. Additionally, SPPs are strictly TM polarized. Thus, a silicon photonic or plasmonic device designed for one polarization will often not have the same performance, or, not work at all for the other polarizations [30]. This is especially the case for high-confinement waveguides where the SOI thickness is 220 nm, as commonly offered by multi-project wafer foundry services.

This means that in addition to the large mode-size mismatch between the optical mode in integrated waveguides and the mode in an optical fiber [32], there is a polarization incompatibility, which needs to be addressed. If not addressed, the transmission and performance of the photonic circuit will be unstable. A straightforward approach is to prevent the problem from occurring. In this case, this would mean to either have the silicon waveguides be polarization-insensitive, or to have the optical mode in the fiber maintain its polarization.

An etched silicon waveguide could in theory be made polarization insensitive, through controlling its width and height accurately. A perfectly square waveguide would still have a TM and TE mode, but their effective indices would be the same if the waveguide is straight. On the other hand, when the waveguide is bent in the plane, for example in a micro-ring resonator, where the goal is to have the same resonance frequencies, the cross-section would need to be slightly rectangular. In a ring resonator, the height and width of the waveguide would need to be controlled with a subatomic precision to prevent
Chapter 1. Introduction

a shift in resonance frequency by more than a fraction of the width of the resonance between the two polarizations [30]. This is neither technologically nor economically feasible. Additionally, if a fiber is to be interfaced with a SPP circuit, there is no choice than to couple light to only one polarization. SPPs are always TM modes and do not have a TE counterpart.

Alternatively, one could make fibers that are polarization maintaining. Polarization maintaining fibers have been a commercial product for some time now and thus would be a viable alternative. However, they tend to have larger dispersion, are more expensive, and would have to be specifically aligned when being connected to the photonics circuit [33]. Thus, while currently used in most research labs, they should be avoided in a large scale integration.

In summary, a solution has to be found to interface an optical fiber with a photonics circuit while removing the polarization incompatibility without putting restrictions on either the fibers or the photonics waveguides. Currently, a widely accepted solution is polarization diversity [30]. The light is coupled to the photonic circuit from the fiber and then split into the TE and TM components. Usually the TM component is rotated to the TE mode and the light is processed in two identical circuits. A recent demonstration of functionality using polarization diversity is an optical clock [34]. Passive functionalities can be realized by utilizing the forward and backward propagating modes as previously demonstrated [35]. However, utilizing the forward and backward components to remove the need for two circuits is limited to simple or passive circuits. Any more complex functionality or even active circuits would require two optical circuits. Thus, the power consumption and space requirements would be doubled for active polarization diversity circuits.

This doubling leads me to believe that a new solution has to be found to overcome the limitations of the current approaches, one that works like an adapter, connecting a fiber to an integrated circuit, where either side can treat the other as a black box. To find, design and analyze such a solution is the motivation of this thesis.

1.4 Thesis Outline

In this introduction, I have introduced two waveguide systems for photonic integration: silicon photonics and plasmonics. I have given a high level overview of their limitations and chances, the state of the art and, most importantly, why we need them for optical on-chip communication. I believe that not only one of these material system will succeed, but they will complement each other in the future. In the last section, the problem of
fiber to waveguide interfacing due to polarization mismatch has been outlined. This thesis will give component and system level solutions to the polarization problem for silicon photonics as well as plasmonics. This solution will allow to interface fibers with photonic circuits efficiently and allow for the next generation of communication transfer.

In the next Chapter (2), the concept of a hybrid plasmonic waveguide is explained, as well as its fabrication. Typical dimensions are given, the advantages of the hybrid plasmonic waveguides are discussed, and fabrication recipes are developed. The design and measurement of a hybrid plasmonic polarization rotator is discussed in Chapter 3. The polarization rotator shows significantly better performance than previous designs and can serve as a component in any solution addressing the polarization mismatch. Chapter 4 talks about another hybrid plasmonic device, the broadband coupler. Its uniquely compact footprint and broadband spectral response are discussed. Then Chapter 5 gives a system level approach to fiber-to-chip interfacing. The approach involves a polarization transparency solution that allows for interfacing fibers to a circuit, where both the fiber and photonic circuit can be optimized independently. To demonstrate this approach, I decided to use well-established foundries and thus was limited to pure silicon photonics. The chapter gives a theoretical understanding, the design of all the components required, and experimental results. In the last Chapter (6), I discuss how to integrate the developed hybrid plasmonic components with the polarization transparency scheme. Other applications for the polarization transparency scheme are given and measured. Finally, the thesis is concluded with Chapter 7, in which a summary of the achievements and possible future directions of the work are given.
Chapter 2

Hybrid Plasmonic Waveguides and their Fabrication

2.1 What is a Hybrid Plasmonic Waveguide?

The hybrid plasmonic (HP) waveguide was first reported in [36] as a compromise between the high confinement of the surface plasmon polariton (SPP) waves and the much lower loss of a dielectric waveguide mode. The hybridization of the mode is illustrated in Fig. 2.1(a). A high index dielectric waveguide is combined with a metallic interface

\[
\begin{align*}
\text{SiO}_2 & \quad + \quad \text{Ag} \quad \text{SiO}_2 \\
\text{Si} & \quad + \quad \text{Ag} \quad \text{Si} \\
\hline
\end{align*}
\]

\(\text{(a)}\)

\[
\begin{align*}
\text{Figure 2.1: Qualitative illustration of the hybridization of the dielectric and plasmonic waveguide modes to form a hybrid plasmonic waveguide mode. (a) Addition of the waveguide structures and (b) addition of the mode profiles.}
\end{align*}
\]
Chapter 2. Hybrid Plasmonic Waveguides and their Fabrication

Figure 2.2: Qualitative pictures of the (a) TE and (b) TM mode of a hybrid plasmonic waveguide.

separated by a spacer region. A HP waveguide always consists of combining these three materials in some way.

The hybridization of the mode is shown in Fig. 2.1(b). The majority of the mode of a dielectric high contrast waveguide is typically contained inside the high-index material. On the other hand, a surface plasmon waveguide has its mode energy at the metal interface where the material losses due to the metal are especially high. The HP waveguide moves the energy out of the high-contrast dielectric into the low-index region and can thus be understood as low index guiding. The newly formed mode ensures strong confinement (the majority of the mode is located within the few tens of nanometer thick spacer region), while having low loss as the mode is moved away from the metal. The decrease in loss can be more then order of magnitude around a wavelength of 1.55 μm. At this wavelength typical metal-insulator-metal waveguides have loss of 5 dB/μm [37], while hybrid plasmonic waveguides will have loss of about 0.1 dB/μm [38].

This hybridization will occur strongly for the vertically polarized (TM) mode. SPP modes have the electric field always orthogonal to the metal surface and do not support a mode with the electric field parallel to the surface. Thus, the metal surface, which is parallel to the top of the silicon waveguide, will provide the hybridization for the TM mode. The TE mode (horizontally polarized) will be mostly unchanged compared to a purely dielectric waveguide, but might move slightly away from the metal into the substrate or even be cut-off, depending on the specific dimensions.

The metal interface will separate the material region in which the TE and TM mode are guided (see also Fig. 2.2). This separation of the modes is important for polarization sensitive devices. More information about the formation of the modes and hybridization of the TM waveguide with the SPP mode can be found in the theses of my colleagues.
Alam [38] and Xiao [39].

Since the invention of the HP waveguide, several new devices have been proposed and realized that utilize the unique combination of mode localization and low loss. Some of these devices are shown in Fig. 2.3. The large number of proposed and realized devices is indicative of the promise HP waveguides show in different applications [37].

In this thesis, the unique properties of the HP mode are used to realize two different devices: an ultracompact broadband polarization rotator and a compact colorless large-bandwidth directional coupler. Both of these devices rely on the fact that the metal has a different influence on the TE and the TM mode of a silicon waveguide: the HP TM-mode is a low-index guided mode in the spacer region, while the TE mode is high-index guided and gets pushed away from the metal. The polarization rotator changes the polarization of the modes by rotating the metal around the waveguide. Due to the separation of the TE and the TM mode, the coupling between these modes, which is usually a source of large crosstalk [44], is suppressed. The directional coupler relies on the influence on the TE mode, which causes enough change to the propagation constant and mode to suppress coupling between two silicon-waveguides.

A number of metals can be used to allow for the implementation of the plasmonic components and from the HP waveguide. The optimal metal will depend on the requirements of the device, available fabrication tools and other restrictions. A commonly used metal is gold, which allows for the implementation of low loss devices [45] but is not CMOS compatible as it will diffuse into the silicon. An alternative, which is used for the devices in this thesis, is silver (Ag). Silver allows for low loss devices, but is not compatible with high temperature processes often employed in CMOS foundries. However, it was easily available at local facilities in contrast to metals used at CMOS foundries. Future devices could be implement with Cu components as already done by other groups [46].

In the next section, I will explain the fabrication procedure, which was developed by myself for fabricating HP waveguides. In the following two chapters, details of the rotator and coupler design are given. Both of these devices rely on a high-quality silicon nanowire waveguide, on which a metal strip with sub-micrometer accuracy is placed at the optimal vertical and horizontal position. Hence, a high quality nano-fabrication procedure is required for good device performance. Figure 3.2 and Fig. 3.7 shows device schematics of the polarization rotator, while Fig. 4.2 shows a schematic for the broadband coupler.
Figure 2.3: A selection of different HP devices: (a) Light concentrator [40]; (b) Polarization beam splitter [41]; (c) Large bandwidth Bragg grating [42]; (d) Electro-optic modulator [43].
2.2 Fabrication of Hybrid Plasmonic Waveguides

2.2.1 Fabrication Overview

The process flow for the fabrication of a hybrid plasmonic waveguide is shown in Fig. 2.4. The fabrication process can be split into four stages (A,B,C,D). First, a number of alignment markers is fabricated on an silicon-on-insulator (SOI) substrate to allow for multiple fabrication steps (stage A). In stage B, the silicon waveguide for dielectric guiding is formed by patterning of an electron-beam resist and reactive ion etching (RIE). Third, the spacer layer of silica is deposited (stage C). Last, a lift-off mask for metal is created, into which metal is deposited, forming the plasmonic guiding (stage D). Now the device is finished, but to protect it from the environment, the sample is then coated with a polymer for protection. To summarize, an alignment ability is created, and then the three material layers for the HP guide are deposited and/or defined (silicon, silica, silver). The order of this section will follow the order of these fabrication stages.

2.2.2 Electron-Beam Lithography and Alignment Markers (Stage A)

To achieve high accuracy in layer definition and alignment between layers (silicon and metal layers) I used electron-beam (e-beam) lithography [47]. In e-beam lithography
the sample is spin-coated with a polymer, which is sensitive to e-beam exposure. The electrons change the solubility of the polymer to allow removal of either the exposed (positive tone) or non-exposed (negative tone) areas using a solvent.

The required pattern is directly written into the resist using an electron beam with an e-beam writer, in this case Vistec EPBPG 5000+. The e-beam writer is essentially a modified scanning electron microscope, which is optimized for writing instead of imaging, but it retains an (somewhat poorer) imaging capability. This imaging capability allows for accurate alignment between layers, as markers can be fabricated on the sample and imaged using the e-beam writer. Thus, a specified layer can be written at an exact position relative to the imaged markers. The achievable accuracy depends on the exact process, but can be lower than the spot size of the electron beam \[4\], which is already only a few nanometers large.

Before starting fabrication of the HP waveguide, a recognizable pattern needs to be created on the sample substrate. To achieve high accuracy in the alignment between layers the pattern should be clearly visible (give good contrast) in the e-beam writer. Thus, a material with a large electron back scattering coefficient should be chosen. I used gold as a metal for the alignment markers \[4\]. The alignment markers were 20 µm by 20 µm large squares placed in a grid spaced at a distance of 500 µm in both \(x\) and \(y\) direction.

A summary of the alignment marker process flow is shown in Fig. 2.5. The markers were fabricated on a SOI substrate with a device layer thickness of 220 nm and a buried oxide of 2 µm (Step A.1). The SOI was spin coated with ZEP-520A, a positive tone e-beam resist (Step A.2). The markers were written into e-beam resist using a Vistec EPBPG 5000+ electron beam lithography system, and developed (Step A.3). After step A.3, any resist exposed to a sufficient number of electrons, also called dose, is removed. After development, I deposited gold using a thermal evaporator (Step A.4) and performed a lift-off using ZDMAC to remove the ZEP and metal that was deposited on top of the resist (Step A.5).
Figure 2.6: Process flow for the silicon nanowire waveguides. The material color coding is in agreement with Fig. 2.4.

The knowledge gained from the improvement of the metal deposition for the SPP waveguide (Stage D), as explained in Sec. 2.2.4, was also used to improve on the alignment marker fabrications. In later samples, a double resist stack of MMA-EL 10\textsuperscript{TM} and PMMA A3\textsuperscript{TM} was used for the alignment markers on the SOI. Gold was replaced by tungsten, where the electron back-scattering signal is slightly worse but the processing time was significantly reduced due to the use of a load-lock sputtering system instead of a thermal evaporator.

2.2.3 Silicon Waveguide Etching and Silica Deposition (Stage B & C)

The samples with alignment markers were spin coated with a 340 nm thick layer of ZEP-520A\textsuperscript{TM} and baked using a hotplate (Step B.1 & B.2). Electron beam lithography was used to write the silicon waveguide pattern into the resist (Step B.3). The pattern was transferred using a SF\textsubscript{6}/O\textsubscript{2} chemistry in an reactive ion etcher (Step B.4). The used etch recipe was originally developed by a colleague \cite{39} and I optimized the recipe further to reduce sidewall roughness and make the sidewalls more vertical. The sidewall roughness was analyzed qualitatively using SEM pictures and the optimization included the tweaking of etch gas flow rates, pressure, and RF power of the etcher.

A number of samples were etched to determine the offset between the waveguide design width of in the layout file and the widths of the fabricated waveguides. The goal was always to produce waveguides with a width of 450 nm. The offset slightly changed throughout my PhD but was about 155 ± 40 nm in my last fabrication run. According to these results, the structure is drawn 155 nm larger in the layout editor than what it was intended to be. In addition to this offset, the width varied by up to 40 nm between different etches with the same recipe. A typically etched silicon waveguide is shown in Fig. 2.7(a).

In the next stage, a plasma enhanced chemical vapor deposition (PECVD) system deposits SiO\textsubscript{2} on the etched waveguides (Step C.1). A standard recipe was used, and
the deposition rate was determined as follows. Silica was deposited on a set of etched waveguide samples. For all samples, the same deposition recipe was used, but with different deposition times. The silica thickness was then measured by means of imaging the cross-section of the coated waveguide using a scanning electron micrograph (SEM). A typical waveguide cross section is shown in Fig. 2.7 (b).

The thickness of the silica on top of the waveguide was of primary interest. An ellipsometer could not measure this film thickness, because one can not focus the light of the ellipsometer on top of the waveguide. I was not sure if the thickness would be different on top of the waveguide and around it. The material on which the silica is deposited can make a difference at the beginning of deposition and as they were different in my case (silica around the waveguide and silicon on top). Additionally, the local conditions are different due to the geometry. Thus, an SEM was used to measure the cross-section and the silica thickness. The deposition rate of the recipe used was determined to be \(~6.9\) nm/min.

### 2.2.4 Metal Deposition (Stage D)

The deposition of the metal layer to form the plasmonic waveguide for the HP waveguide proved to be the most challenging part of the fabrication. The general process flow for the metal deposition is summarized in Fig. 2.8. I started with the etched silicon waveguides and silica spacer (Step D.1). The e-beam resist was spin coated (Step D.2), and the e-beam writer was used to write the wanted pattern. After development the resist had voids (Step D.3) into which the metal could be deposited to form a surface plasmon interface with the underlying silica.

An e-beam evaporator (Step D.4) deposited the metal onto the samples. In an e-beam
evaporator, an electron beam under high vacuum is directed onto a target that consists of the metal to be deposited. Under the electron bombardment, atoms of the target are ejected into vacuum and travel upwards. The sample is mounted above the target in the path of the atomic beam, which is emitted by the target. The advantage of the e-beam evaporator is its high directionality. Thus, only small amounts of metal will be deposited on sidewalls, which improves lift-off [50]. After deposition, a standard solvent (acetone) removes the resists so that the metal was left only in the areas needed, i.e. on top or on the side of the silicon waveguide (Step D.5).

Usually one needs a resist [51] thickness at least twice the metal thickness to be deposited. At the beginning, a thick ZEP layer was used as resist. In which case a reduced spin speed during coating led to the wanted increase in layer thickness. To improve adhesion between the silver and the silica interface, about 2 nm of chromium were deposited first. A 150-250 nm layer of silver was then deposited. The thickness
depended on the device to be fabricated. ZDMAC\textsuperscript{TM} was used to strip the resist and perform a lift-off. To reduce the risk of removing the wanted metal area, the samples were soaked overnight and then put in an ultrasonic bath for only a few seconds.

The results of this deposition with the goal of building a HP rotator are shown in Fig. 2.9. Due to the vertical sidewalls (slightly v-grooved) of the ZEP the quality is rather poor. Most often, the deposited metal on top of the resist formed bridges with the metal directly on the silica, leading to the following problems:

- Despite aiming for a \textit{soft} lift-off by soaking the samples overnight, often the silver would lift-off (see Fig. 2.9(b)).

- Most often, a thin layer of chromium around the wanted area remained in unwanted areas (marked with red arrows).

- The silver surface in the center of Fig. 2.9(a) is very rough and somewhat bubbly.

To improve the quality of the silver and the reproducibility of the process, I developed a new resist recipe, where a double lift-off profile is used to prevent both the chromium on the side and to make sure that the silver remains on the sample. A double lift-off uses two resists spin coated on top of one another. The bottom resist is chosen for a higher sensitivity to e-beam exposure than the top resist (for positive tone resists). A higher sensitivity means that a lower electron dose is needed for a similar change in solubility of the polymer. After development, the resist stack forms an undercut profile. This undercut stops the formation of bridges between the two metal layers.

\textbf{Figure 2.10:} \textit{SEM picture of a double lift-off after metal deposition (Ag) before removal of the the resist stack.}
Figure 2.11: (a) An SEM of a polarization rotator using the improved double lift-off recipe. (b) A close-up of a deposited metal surface (different sample than (a)).

A cross-section of deposited metal in a double lift-off process before lift-off is shown in Fig. 2.10. Here I used a standard silicon wafer as substrate. For the double resist stack first MMA-EL 11 and then PMMA A3 on top are used; where MMA-EL 11 is a copolymer which has a significantly larger sensitivity. The resists form a perfect undercut and thus there is no connection between the silver on the silicon and on top of the resist. Additionally, there is no chromium visible on the sides of the silver.

The aspect-ratio of the deposited metal is limited to about two. Thus, one can only deposit metal twice as high as the pattern is wide. During the deposition, the gap in the resists closes. This gap closing is either due to metal deposited on the sides of the resists or because of sample heating during evaporation that might allows the resist to slightly reflow. Further research would be needed to be certain about the mechanism; however, the closing of the resist gap was not a concern for my devices. Before closing, the metal thickness would typically reach \( \approx 300 \) nm, which was sufficient for all the features required.

The optimized recipe was then used to fabricate a new set of polarization rotators, shown in Fig. 2.11(a). A square is added to the side of the rotator (outside the functional area) in order to increase the contact area. This further reduces the risk of lifting off the silver. There is still a small amount of chromium around the device (e.g. left bottom corner of device), but the amount is reduced significantly compared to the single lift-off recipe. With the improved process, I do not have to soak the samples, but can use an ultrasonic bath of acetone immediately, which reduces the processing time.

Additionally, I was able to improve the silver surface, as visible in Fig. 2.11(b). This
was possible due to an increase in the deposition rate of the silver. It might be counter-intuitive that an increase in deposition rate helps to improve the surface; however, the samples in the e-beam evaporator are not temperature controlled and get very hot during deposition. Silver layers with dimensions of a few hundred nanometers tend to form clusters \[52\] when heated. Thus, by increasing the rate, the time the sample spends in the chamber is reduced, which limits the sample temperature and prevents clustering.

### 2.2.5 Top Oxide Cladding

The effect of silver aggregating into clusters turned out to be a problem for my post-processing step as well. After metal deposition and lift-off, I coated my samples in a thick silica layer. This was done to increase the sample life by preventing silver oxidation and to better match the simulated device. However, during a standard PECVD deposition, the sample reaches a temperature of about 300 °C, more than enough for the silver to form clusters, as shown in Fig. 2.12. The left picture (a) shows silver after lift-off before silica deposition and the right (b) is after a standard deposition. The silver seems to become very rough and of a bad quality.

Thus, instead of PECVD deposition, a commercially available flowable oxide (FoX-15\textsuperscript{TM}) is spin-coated. After testing, I discovered that the transition temperature for the silver to form clusters is about 110 °C and is time-independent. Hence, the flowable oxide was baked on a hot-plate for more than 10 minutes at 110 °C to remove any solvent. This temperature is below the glass transition temperature of the flowable oxide, and silicon
waveguides covered with the flowable oxide did not show increased loss compared to air or PECVD silica covered waveguides.

A summary of the final fabrication process steps, including recipe parameters for all machines, can be found in Appendix A.

2.3 Simulation of a Hybrid Plasmonic Waveguide Device

A commercial (Lumerical) 3D finite difference time domain (FDTD) code is used to simulate the performance of the hybrid plasmonic waveguide device designed in the following chapters. Here, I discuss the performed convergence analysis of the simulation. The convergence analysis was done to ensure high accuracy of the simulation results. For information on the FDTD algorithm itself please refer to Ref. [53].

As mentioned, FDTD can provide high accuracy results for the optical response of integrated optical components if the correct mesh settings are chosen. To ensure this is the case, one needs to do a convergence analysis. In a convergence analysis a typical device performance parameter is chosen and its dependence on different mesh settings is analyzed. Here, a convergence analysis is explained using the example of the HP broadband coupler designed in Chapter 4. The device performance parameter used is the optical power at one of the output ports. This parameter should converge towards one value for smaller mesh settings, the faster it does that, the better the chosen mesh method and the smaller the error in the simulation is.

In general, the more mesh steps per wavelength are used the more accurate the simulation will be. However, this is done at the cost of an increase in computation time. Additionally in Lumerical FDTD one can chose between a number of different mesh algorithms, which differ in how they treat the boundary between materials. More details on these methods can be found in Ref. [54]. Lastly, to further improve the accuracy, one can additionally override the meshing with a higher accuracy in specific regions of interest. This overriding is done here for the silica spacing region between the metal and the silicon of the HP waveguide in some simulations. In summary, the number of mesh steps per wavelength are varied for a number of meshing methods are compared, with and without mesh override.

The results of a convergence analysis performed on the broadband coupler are shown in Fig. 2.13. The transmission is plotted against the mesh accuracy one can chose in the FDTD code provided by Lumerical for different mesh algorithms. The simplest
method of staircase mesh also shows the worst performance as shown by the light blue and orange curve in Fig. 2.13. Over the accuracy region of interest the results do not converge and show strong oscillations. Conformal meshing, even without mesh override, (dark blue curve) already shows a significant improvement, but the convergence remains slow. Thus simulations could be run with a very small mesh step (i.e. 20 points per wavelength), this would mean though that they would take very long. Lastly, combining conformal meshing method 1 with a mesh override (green curve) provides a very good convergence, the optical transmission changes by less than 0.005 for more than 14 mesh steps per wavelength. This picture is consistent with other devices. Thus typical design optimization were run with this setting.

Figure 2.13: Convergence of the FDTD simulation of a hybrid plasmonic waveguide
Chapter 3

Integrated Hybrid Plasmonic Rotator

My first project using a hybrid plasmonic (HP) waveguide was a polarization rotator for integrated silicon photonics circuits. The idea was originally developed by my colleague Alam [38] and myself. The simulations, fabrication and measurements were performed by myself. The work in this chapter has been published in Ref. [55] and Ref. [56].

This chapter begins with a review on previous (dielectric) integrated polarization rotators. In the following section, the design for a hybrid plasmonic rotator is presented and physical intuition of its operation are given. Lastly, experimental results are presented showing the good performance of the hybrid plasmonic rotator.

3.1 Previous Integrated Polarization Rotators

A polarization rotator is a key component for polarization diversity [57]. However, it has been an ongoing challenge to design an integrated, compact, and low-loss rotator using only dielectric materials [58, 44, 59] around a wavelength of 1.55 µm. So far, most designs have been based on mode interference [58] or adiabatic mode evolution [44, 59]. Both methods come with their own sets of advantages and limitations.

Adiabatic mode evolution schemes require rather long device lengths (>100 µm) to achieve sufficient extinction ratios and low insertion losses. Furthermore, they usually require uncommonly thick silicon waveguides [59] or additional material layers [44]. An example of a mode evolution rotator is shown in Fig. 3.1 (a) fabricated by Chen et al. [44]. A Si₃N₄ layer is deposited on top of a silicon waveguide and a horizontal offset is introduced along the propagation direction. This causes the TM-mode at the input to rotate to the TE mode of the silicon waveguide. The total device length was 420 µm and
Chapter 3. Integrated Hybrid Plasmonic Rotator

**Figure 3.1:** (a) An example for a dielectric based mode evolution polarization rotator [44]. (b) A mode interference polarization rotator [60].

An insertion loss of about 1 dB with a polarization extinction ratio (PER) of 9 dB over a 80 nm spectral bandwidth was achieved.

On the other hand, devices based on mode interference are often short (∼10 µm), but are sensitive to fabrication imperfections and tend to have a limited spectral bandwidth (∼25 nm) [58]. Figure 3.1 (b) shows a mode-interference rotator that has been previously proposed and demonstrated [60]. At the interface between the silicon core and the 2nd core (see Fig. 3.1 (b)) the incident light (TM) excites two modes which are polarized at 45° with different propagation constants. As these modes propagate in the 2nd core they interfere. The length of the 2nd core is chosen such that the diagonal modes interfere constructively to form a TE mode corresponding to a polarization rotation of 90°. Their experimental results are comparable to the mode evolution scheme with 1 dB insertion loss and 10 dB polarization extinction ratio (PER). While this demonstrated rotator is significantly shorter (35 µm) compared to mode evolution designs, the spectral bandwidth is also reduced to about 30 nm.

Recently, it has been suggested to use surface plasmon polaritons (SPPs) to reduce the length of a rotator [61]. For example, Zhang et al. demonstrated an ultracompact rotator (3 µm) based on SPPs, but their design showed a high insertion loss (>11 dB) [61].

In summary, while a number of designs for polarization rotation have been demonstrated, they all come with disadvantages. The goal would be to have a compact design with large spectral bandwidth and low insertion loss, combining the advantages of the dielectric schemes as well as the SPP design.
3.2 Numerical Simulations: Design Version 1

The work in this section has been published in Ref. [56].

To overcome the limitations of previous integrated polarization rotators I propose to use a HP waveguide to design an ultra-compact integrated polarization rotator operating at 1.55 $\mu$m. The proposed HP polarization rotator combines the advantages of both mode evolution and mode interference schemes, while at the same time showing a low insertion loss ($\sim$2 dB) and high PER ($\sim$15 dB). The proposed polarizer can be made exceptionally short (5 $\mu$m), while showing performances better or comparable to other state-of-the-art designs.

Figure 3.2: (a) Schematic top-view of the simulated device. The three sections (input taper, rotation section, and output taper) are indicated with black dashed lines. The brown lines indicate the positions for the mode profiles in Fig. 3.3 (b) 3D schematics (not to scale) of the rotator. Green corresponds to silicon and gray to silver. The silica spacer has been removed for clarity [55].

Figure 3.2 shows a design schematic for a polarization rotator. The rotator consists of three sections. The first section is a short taper that transforms the TM silicon waveguide mode into the TM polarized HP mode. A silica spacer layer (omitted in Fig. 3.2 for clarity) separates the silver from the silicon throughout the device. A significant portion of the HP mode energy is located in this silica spacer. The polarization rotation happens in the rotation section, where the silver layer moves sideways and downward relative
to the silicon nanowire. Thus, the silver rotates around the silicon waveguide. In the last section, the silver is terminated and the silicon waveguide linearly tapers out to its original width. The input and output waveguides of the rotator are standard silicon waveguides with a thickness of 220 nm and a width of 450 nm. The silver layer has a thickness of 200 nm. The silver is located above and on the side of the silicon, separated from the silicon by a silica spacer layer. Different spacer thicknesses between 80 and 150 nm were considered during the design. Although silver is not a perfect conductor in the near infrared, it can be still considered a good conductor (due to its relatively low losses) and thus the electric field will stay normal to the silver surface. The hybrid mode will rotate with the rotation of the silver layer around the silicon waveguide.

**Figure 3.3:** (a) Effective index evolution along the rotation section for the rotating TM to TE mode as well as its orthogonally polarized counterpart TE to TM. The position is normalized and independent of the final rotator length. (b) Mode profiles at three locations in the rotator, indicating how the mode follows the metal rotation around the waveguide. The positions at which the profiles are calculated are indicated in the schematics (Fig. 3.2) and in the effective index evolution (a) \[55\].

Figure 3.3 (a) shows the effective indices for the desired TM → TE mode, as well as the undesired TE → TM mode at a vacuum wavelength of 1.55 µm as a function of normalized distance in the rotation section. The distance is normalized where a value of 0 corresponds to the input and 1 to the output. Additionally, three specific positions
(i), (ii), and (iii) are indicated in the plot as well as Fig. 3.2 (a). In a mode-evolution scheme the required length for a good device performance is governed by the difference in effective index between the mode that is being transformed (here: TM → TE) and the next order mode (here: TE → TM) [44]. In this design the minimum difference is always larger than 0.3, which is a tenfold increase compared to previous mode evolution dielectric designs [44]. As we will see later, this tenfold increase directly relates to a more than tenfold reduction in device length.

The rotation from a TM mode to a TE mode is visible in the mode profile (normalized amplitude of the electric field) shown in Fig. 3.3 (b) for the positions indicated in Fig. 3.2 (a). At position (i), the input of the rotation section, the mode is a HP TM mode and most of the energy is located in the spacer region on top of the waveguide. As the metal rotates around the waveguide (position (ii)), the light follows the metal and the electric field points diagonally. At the end of the rotation section the light is rotated to a hybrid TE mode and located on the side of the silicon waveguide. After termination of the metal a dielectric silicon TE mode is formed.

To optimize the device’s performance, specifically the insertion loss and polarization extinction ratio, a number of critical device dimensions were varied and the performance was analyzed. The 3D finite difference time domain (FDTD) solutions software from Lumerical [62] was used for the simulations. I determined the mesh density and simulation size using a convergence analysis and chose a setting with high accuracy, while ensuring that the computation time is small enough to ensure fast convergence towards a good design (See Sec. 2.3). Unless otherwise indicated, all simulations presented here are for a wavelength of 1.55 µm. For a suboptimal device design, the power in the output waveguide will not only be located in the wanted TE mode but some power might also remain in the TM mode. Thus, the power in the two polarizations needs to be separated. The power in the TM polarization was evaluated according to [63]

\[
P_{TM} = \text{Re} \left[ \frac{\int (\vec{E}_{3D} \times H_{TM}^*)z dA \cdot \int (\vec{E}_{TM} \times H_{3D}^*)_{z} dA}{\int (\vec{E}_{TM} \times H_{TM}^*)_{z} dA} \right], \tag{3.1}
\]

Here, \( E_{3D} \) and \( H_{3D} \) are the electric and magnetic fields respectively extracted from the 3D-FDTD device simulations at the output waveguide. \( E_{TM} \) and \( H_{TM} \) are the fields of the TM mode of a silicon waveguide with the same dimensions (220 nm×450 nm) calculated using an FEM solver software (COMSOL 4.2, [64]). A similar expression was used for the TE polarization. The integral in Eq. 3.1 is performed over a cross-sectional area of the output and \( z \) is the light propagation direction. The extracted power in the respective polarizations was used to calculate the extinction ratio. The polarization
extinction ratio (PER) is defined as the ratio of the transmitted powers in the TM and TE modes and

\[ \text{PER} = -10 \log_{10} \left( \frac{P_{TE}}{P_{TM}} \right). \tag{3.2} \]

\( P_{TE} \) and \( P_{TM} \) are the powers in the output waveguide calculated according to Eq. 3.1.

The insertion loss (IL) was extracted as well where the power in the wanted waveguide mode (TE) is normalized to the source power in the simulation. In all simulations, the insertion loss is the total loss going from the silicon waveguide TM mode to the TE mode of the same Si waveguide. This includes the reflection loss to the hybrid mode at the interface to the input taper, both (input and output) taper losses, polarization mode conversion losses, and propagation losses due to absorption in the metal.

In the following simulations, the input taper has a length of 650 nm and contributes <0.3 dB loss to the total insertion loss. The output taper has a length of 1.5 µm and
has a similar loss of $<0.2$ dB.

I began optimizing the performance of the rotator by varying the width of the silicon nanowire in the rotation section (see Fig. 3.2). The results of the optimization are plotted in Fig. 3.4. For these simulations, the rotator had a total device length of $5.2 \mu m$ and the silica spacer was $80$ nm thick. The insertion loss is plotted in Fig. 3.4(a) as a function of the width of the silicon waveguide at the input of the rotation section (region marked (i) in Fig. 3.2(a)) and the width of the output (region marked (iii) in Fig. 3.2(a)). A minimum insertion loss of $2.1$ dB can be achieved for an input width of $220$ nm and an output width of $300$ nm. A linear taper is used along the rotator section to match the two widths. The losses remain low for usual fabrication tolerances of $\sim 30$ nm, but increase significantly for larger deviations. The minimum loss coincides with a square cross section of the silicon waveguide at the input.

Figure 3.4(b) shows the extinction ratio again as a function of silicon waveguide widths. The highest extinction ratio is $15$ dB for an input width of $220$ nm and an output width of $270$ nm. While the optimal input width ($220$ nm) is the same for minimum insertion loss and maximum extinction ratio, the output width differs by $30$ nm. A wider cross section will increase the mode confinement in the silicon, thus the metal will be less effective in rotating the mode. However, for a narrow silicon waveguide width, the insertion loss due to the metal as well as losses due to the taper transitions increase.

To further improve the device’s performance, I simulated different device lengths and spacer thicknesses (Fig. 3.5), where the width of the silicon waveguide and the input and output of the rotation section were set to achieve the optimum insertion loss (input width = $220$ nm, output width = $300$ nm).

The losses of the simulated device show three distinct regions. (I) If the rotator length is too short ($\lesssim 3.5 \mu m$), the mode is not adiabatically rotated and, thus, power is coupled and lost to other modes. (II) If the rotator is too long ($\gtrsim 5.5 \mu m$), it will suffer from material losses due to the silver. (III) The optimal device length depends on the silica spacer thickness, and is approximately between $3.5$ and $5.5 \mu m$. The $3$ dB bandwidth of the extinction ratio is $>150$ nm, thus the design shows a broadband characteristic as expected for a mode evolution scheme. In summary, the total device length can be as short as $5 \mu m$, while reaching a polarization extinction ratio $>15$ dB and showing a low insertion loss of $2.1$ dB. The extinction ratio can be further improved by using the rotator in series with an integrated polarizer similar to the one reported in [65].
Figure 3.5: (top) Polarization extinction ratio between the TM and TE modes for the proposed rotator as a function of device length, and (bottom) insertion loss for the same device. Symbols represent simulation results, while the curves are guides for the eye [55].

3.3 Experimental Results: Design Version 2

The work in this section has been published in [56].

3.3.1 Redesign for Easier Fabrication

After developing a fabrication procedure and obtaining SEM pictures which showed good devices as visible in Fig. 2.11, my experimental results for the device were slightly below expectations. By comparing my simulated structure with the fabricated structure, I realized the problem.

Figure 3.6(a) shows the design I was simulating previously. From the SEM pictures of the fabricated devices, I noticed that the silver does not rotate as smoothly as expected around the silicon waveguide, but has a sharper tip when introduced on the lower level (compare to Fig. 2.11). When introducing this sudden step in the simulations as shown in Fig. 3.6(b), the simulated results matched closely the ones I experimentally obtained, with a PER of only 3 dB. The problem seemed to be the sudden introduction of metal, which forms a tip on the side of the waveguide (indicated by a red arrow in Fig. 3.6(b)). This tip acts as a light concentrator and radiates light. I decided to try to redesign the rotator in order to mitigate the problem.
Figure 3.6: 3D view from the simulation showing (a) the previously simulated device and (b) the simulated design to closer represent the fabrication. Green corresponds to silicon, grey is silver, and silica has been removed for clarity. The red arrow in (b) indicates the metal tip as explained in the text.

To remove the tip, I introduced the metal from the start on both the side and the top of the silicon waveguide. This improved design is shown in Fig. 3.7. Besides having a better performance the device is also easier to fabricate, as the metal can now be significantly wider. The metal can extend towards the side of the waveguide (here: top of Fig. 3.7(a)) without affecting device performance. This increases the minimum feature size and thus makes fabrication easier.

I ran the same optimization for the new design as the earlier one and also optimized the lengths of both the input and output taper. The results for the length scan of the rotation section for three spacer thicknesses (90 nm, 130 nm, 170 nm) are shown in Fig. 3.8. The results are similar to the previous design, and again three distinct regions are visible: (I) lossy region due to non-adiabatic conversion, (II) optimal conversion with good performance, (III) high loss due to material loss.

3.3.2 Optical Characterization Setup

The new design was fabricated using the procedure outlined in section 2.2. For characterization a commercial broadband light source (AFC BBS 1550™) is used. A polarization beam splitter (PBS) sets the input polarization state to TM and a free-space coupling setup couples the light in and out of the silicon waveguides. The two output polarizations are separated with a second PBS and are measured separately. An Ando optical spectrum analyzer (OSA) AQ6317B™ measures the transmitted light. The measured spectra are normalized with the spectrum of a silicon waveguide without polarization rotator, separating the insertion loss of the rotator itself from the waveguide propagation
Figure 3.7: (a) Schematic top-view of the fabricated device. The three sections (input taper, rotation section, and output taper) are indicated with the dashed lines. (b) 3D schematics (not to scale) of the rotator indicating the input and output polarization states. Green corresponds to silicon and gray to silver. The silica spacer has been removed for clarity. (c) SEM view of the finished rotator before the top cladding is deposited [56].

and coupling losses and other setup losses. The waveguides without rotators had the same length as the one with rotators and where fabricated on the same chip. The loss for the polarizations was different with an excess loss of 7 dB for the TE polarization, which includes coupling to the waveguides from free space and propagation loss. Typical waveguide propagation losses where 1-2 dB/mm.

I calculated the transmission \( T \) and thus the insertion loss for the measured HP rotators according to,

\[
T = \frac{2P_{\text{Rot}}^{\text{TM} \rightarrow \text{TE}}}{P_{\text{WG, TM}} + P_{\text{WG, TE}}}. \tag{3.3}
\]

Here, \( P_{\text{Rot}}^{\text{TM} \rightarrow \text{TE}} \) is the measured transmitted power of one waveguide with a polarization rotator for TM polarized input light to TE output light, and \( P_{\text{WG, TM, TE}}^{\text{avg}} \) is the averaged transmitted power of silicon waveguides without polarization rotators for the TM and
Figure 3.8: Polarization extinction ratio (top) between the TM and TE modes for the proposed rotator as a function of device length, and insertion loss (bottom) for the same device. Symbols represent simulation results, while the curves are guides for the eye [50].

Figure 3.9: Schematic of the linear setup used to characterize the HP polarization rotator.
$TE$ polarization respectively. The factor of 2 in the numerator is due to the normalization of the silicon waveguides; the power of the two polarizations is accounted for by half. The polarization extinction ratio ($PER$) was calculated according to

$$PER = \frac{P_{\text{Rot}}^{TM \rightarrow TM}}{P_{\text{Rot}}^{TM \rightarrow TE}} \cdot \frac{P_{\text{WG}}^{TM} + P_{\text{WG}}^{TE}}{2 \cdot P_{TM}^{WG}},$$

(3.4)

where $P_{\text{Rot}}^{TM \rightarrow TM}$ is the measured transmitted power for TM polarized input to TM output polarization with polarization rotator. The first part of equation (3.4) is the polarization extinction ratio as usually defined [59], while the second part is a normalization required to account for different propagation losses in the silicon waveguide connecting to the device and coupling to the silicon waveguide from free-space.

The normalization is only done, because it is not possible to put a laser right in front of the device and a detector directly behind it. Thus the normalization only accounts for losses that are inherent to the measurement setup. The defined transmission and PER include any losses associated with the rotator itself, such as metal loss, reflections, roughness, coupling to free space mode, and others.

### 3.3.3 Measurement Results

A scanning electron microscope picture of the measured rotator before coating of the top oxide cladding is shown in Fig. 3.10(a). The silver is visible first on top of the waveguide and at the end of the rotator only on the side as wanted. Despite using a double lift-off recipe, there is a small amount of chromium around the device. The sidewall roughness of the deposited silver is minimal.

The measured insertion loss and polarization extinction ratio in dB as a function of wavelength are plotted in Fig. 3.10(b). The spectrum is shown for a device with a rotation section length of 3.7 $\mu$m. After including tapers, the total device length is 5.85 $\mu$m for this device. The rotator shows a truly broadband response with an insertion loss below 3.5 dB for more than a 90 nm bandwidth around 1.55 $\mu$m and a polarization extinction ratio $>7$ dB for the same wavelength range. The spectrum is shown for the device with optimum performance (3.7 $\mu$m long).

The normalized insertion loss at a wavelength of 1.55 $\mu$m is plotted in Fig. 3.11 (red curve) as a function of the length of the rotation section. A minimum loss of 1.0 dB is reached for a rotation section length of 2.3 $\mu$m. The polarization extinction ratio is plotted on the same figure (blue curve) and reaches a maximum of 11.2 dB for the same section length (2.3 $\mu$m). Shorter devices show worse performance (smaller extinction ratio, higher
Figure 3.10: (a) SEM picture of one of the finished rotators before the final top cladding is deposited. This device has a length of 5 µm. (b) Polarization extinction ratio (red curve) and insertion loss (blue curve) spectrum for a rotation section length of 3.7 µm and a spacer thickness of 140 nm [56].
insertion loss), because the device is too short to rotate the mode adiabatically; thus a significant part of the light remains in the input polarization state (TM). For longer devices the material loss due to the metal becomes significant, this absorption in the metal increases the insertion loss, and thus reduces the extinction ratio.

All the fabricated devices were measured and are plotted in Fig. 3.11. As visible, while there is a slight variation of performance between the devices, they all perform as expected. Thus the fabrication yield is very high. The adiabatic design of the transition helps to ensure that despite a non-perfect fabrication, the rotator works as expected.

In summary, as discussed in this chapter, I have designed and experimentally demonstrated an ultra-compact hybrid plasmonic polarization rotator. The demonstrated device has an extinction ratio of \(>11\) dB and a low insertion loss of 3.6 dB with a spectral bandwidth of \(>90\) nm for a total device length of 4.5 \(\mu\)m. The rotator shows significantly reduced losses compared to a previously reported surface plasmon rotator \([61]\). The transmission and extinction ratios are comparable to purely dielectric-based devices \([44]\) while my hybrid rotator is an order of magnitude shorter.
Chapter 4

Hybrid Plasmonic Broadband Coupler

In this chapter a compact, broadband directional coupler using a hybrid plasmonic (HP) waveguide is proposed and realized. The coupler uses an asymmetric section with a HP waveguide to compensate for the spectral dependence of the coupling between two identical silicon waveguides, by introducing a phase difference between the fields in the two waveguides.

First, a design for the TM polarization of a silicon nanowire is presented, where an efficient 2D design algorithm is derived to allow for fast design convergence. A second design for the TE mode is then shown and its fabrication and measurement results for the TE mode are presented.

The broadband coupler was originally proposed by my colleague Alam [38] and he also performed some of the finite difference time domain (FDTD) simulations using a code from Lumerical [62] for the TM polarization design. My work includes the development of a fast 2D design algorithm for the coupler and the simulations, fabrication, and measurements for the TE polarization coupler.

4.1 State of the Art: Integrated Couplers

A directional coupler is a very important component for many applications in integrated optics, ranging from optical communication systems [69] to biosensing [70]. The simplest form of directional coupler consists of two identical waveguides separated by only a small gap to allow the light to couple between the waveguides. An optical microscope picture of such a standard directional coupler is shown in Fig. 4.1(a). This simple design is, however, very sensitive to the wavelength of operation. Although this wavelength dependence can
be useful for implementing devices such as optical filters \[71\], it limits the usefulness of the directional coupler for many other applications where a broadband response is required, for example optical sensing and passive optical networking.

To increase the spectral bandwidth of coupling, and to improve the tolerance to fabrication imperfections, a number of designs have been proposed. The coupler can: be made asymmetric \[72\]; use a grating \[73\]; or have a bend in one arm of the coupler \[74, 75\]. These approaches significantly increase the length of the coupler (over several hundred microns), and most of these designs are for low index contrast systems, e.g., glass or fluorinated ployimide, which limits their usefulness.

One other alternative is the adiabatic coupler approach. It uses two waveguides with different widths and brings them within close proximity. As the widths of the waveguides are equalized, the modes of the single waveguides are transformed into supermodes. In contrast to a standard directional coupler, light from one waveguide will only excite one supermode, thus there is no spectral or length dependent beating pattern between the supermodes, which usually limits the spectral bandwidth. A schematic of an adiabatic coupler with the mode excitation is shown in Fig. 4.1(b). Adiabatic couplers have shown to have a large operating bandwidth (\( \leq 100 \text{ nm} \)) and are very tolerant to typical fabrication imperfections; however, they are typically longer than 150 \( \mu \text{m} \). A more detailed discussion on adiabatic couplers with a design optimization is given in Section 5.4.3.

A multimode interference (MMI) coupler works very differently from the previously mentioned couplers. All of the aforementioned couplers work by bringing two (single mode) waveguides of varying dimensions into close proximity to facilitate coupling. An MMI coupler, in contrast, uses a very wide waveguide with multiple modes and takes advantage of a self imaging phenomena in the multimode waveguide when excited by a single-mode waveguide \[76\]. An MMI coupler can be made very short (around 15 \( \mu \text{m} \)) but the MMI coupler only has a spectral bandwidth of \( \sim 20 \text{ nm} \) and has tight fabrication
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4.2 Device Principle

The power transfer ratio of a directional coupler depends on the ratio of field amplitude at the two inputs and their relative phase. A cascade of directional couplers, where the phase between the couplers is appropriately chosen, can be wavelength insensitive. In this approach, by tuning the length of the first coupler and the length of the phase delay line, one controls the input field amplitude and phase for the second coupler in such a way that it cancels out the wavelength dependence of the first coupler section [74]. The required bends and two couplers usually require long device lengths in purely dielectric designs. In contrast, in a HP coupler a short asymmetric section, as shown in Fig. 4.2(c), can act as the phase delay line between the two couplers. As shown in later sections, such a design allows us to achieve a very broadband response using a very short device length. A top view of the proposed broadband directional coupler is shown in Fig. 4.2(a). The device tolerances [77]. A schematic of a 1x2 MMI is shown in Fig. 4.1(c).

As discussed, while a larger number of designs exist for coupling light between waveguides, their usefulness is limited by the large amount of real estate they require on the chip, or by their small spectral bandwidth. In this chapter, an alternative coupler is presented, where a HP waveguide section is used to overcome the limitations of limited spectral bandwidth while remaining compact in size.

\[ \text{Figure 4.2: (a) Top view of the broadband directional coupler. Dashed lines show the positions of power monitors used in finite difference time domain (FDTD) simulation for calculating power in the output waveguides. (b) Cross section of the first and third silicon coupler sections. (c) Cross section of the second section [78].} \]
consists of three sections: the first and third sections are symmetric directional couplers consisting of two identical silicon waveguides (Fig. 4.2(b)) and the middle section is an asymmetric section consisting of a silicon waveguide and a HP waveguide (Fig. 4.2(c)).

To connect the directional coupler with other on chip devices, waveguide bends must be used at the input and output of the proposed coupler. Because of the high confinement of silicon waveguide modes, the loss due to bends is not very large even for a small bend radius. Furthermore, due to the high mode confinement, coupling will be negligible in the bend regions. For example, in the case of 6 $\mu$m long input and output bends, the coupling ratio changes by less than 2% for the TM design. By excluding the waveguide bends in the simulations, a significant saving in time and use of computational resources is achieved without sacrificing much accuracy.

### 4.3 2D Design Algorithm

The key characteristic used for evaluation of coupler performance is the power transfer ratio, which is defined as

\[
\eta = \frac{P_A}{P_A + P_B},
\]

\[
\nu = \frac{P_B}{P_A + P_B},
\]

where $P_{A,B}$ are the power at WG (waveguide) A and B respectively as defined in Fig. 4.2. In general, the power at the outputs is wavelength dependent and thus $\eta$ and $\nu$ will be wavelength dependent.

To improve the convergence towards an optimal broadband HP coupler design, I developed a simplified 2D model which I will outline below. As shown in Fig. 4.2 the coupler consists of three waveguide sections with lengths $L_M$, where $M \in [1, 2, 3]$. Within these sections the waveguide profile is unchanged along the direction of propagation. Thus, the optical properties of each section can be fully understood by calculating the mode profile of each section. The whole coupler, which is a combination of the three sections, can then be understood using a transfer matrix approach [63].

I will assume that in this case one can limit oneself to two modes (with one polarization) for each section: the odd and even supermode of one polarization. Depending on the design I will limit myself to the TE or TM polarization and neglect any coupling between the polarizations. As we will see, for this device this is a good approximation.
The light at any point along the structures can be described by the following complex vector
\[
\begin{pmatrix}
a_1 \\
a_2
\end{pmatrix},
\tag{4.3}
\]
where \(a_i\) are complex numbers to describe the amplitude and phase of the mode at a specific point along the coupler. Within each section light propagates and is distributed between different modes with their respective propagation constant, which is described by the following propagation matrix
\[
\vec{P}_M = \begin{pmatrix}
e^{i\beta^+_M L_M} & 0 \\
0 & e^{i\beta^-_M L_M}
\end{pmatrix},
\tag{4.4}
\]
where \(\beta^+_M/\beta^-_M\) are the propagation constants of the section \(M\) of the even (+) and odd (−) supermode. The coupling between sections and thus between different waveguide modes is calculated using a coupling matrix,
\[
\vec{T}_{12} = \begin{pmatrix}
c_{11} & c_{21} \\
c_{12} & c_{22}
\end{pmatrix},
\tag{4.5}
\]
where \(c_{ij}\) are the coupling coefficients that determine the coupling between the mode \(i\) of the previous section and \(j\) of the following sections. They are calculated using a power overlap integral \([79]\),
\[
c_{ij} = \Re \left[ \frac{\int (\vec{E}_i \times \vec{H}_j^*) z dA \cdot \int (\vec{E}_j \times \vec{H}_i^*) z dA}{\int (\vec{E}_i \times \vec{H}_i^*) z dA \cdot \int (\vec{E}_j \times \vec{H}_j^*) z dA} \right],
\tag{4.6}
\]
where the numerator represents the coupling between the modes, while the denominator normalizes the powerflow of each modes.

The output of the HP coupler is then calculated by propagating the light through the structure, i.e. multiplying the matrices, where reflections are neglected.
\[
\begin{pmatrix}
a_{End} \\
b_{End}
\end{pmatrix} = \vec{P}_3 \cdot \vec{T}_{12} \cdot \vec{P}_2 \cdot \vec{T}_{12} \cdot \vec{P}_1 \cdot \begin{pmatrix}
a_{Start} \\
b_{Start}
\end{pmatrix},
\tag{4.7}
\]
where the components of \(\tilde{a}_{end}\) are the field amplitudes of the odd and even supermode. The power output of the coupler is then calculated according to,
\[
A_{Output} = |a_{Output}|^2 = \left| \vec{T}_{13} \begin{pmatrix}
a_{End} \\
b_{End}
\end{pmatrix} \right|^2.
\tag{4.8}
\]
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Figure 4.3: Guided power density profiles of the TM modes of the directional coupler at 1.55 m. (a) Odd and (b) even supermodes in the silicon waveguide section. (c) and (d) even and odd modes in the asymmetric hybrid section. The boundary of various layers are shown by dashed lines [78].

Here $A_{\text{Output}}$ is the power at output waveguide A (Fig. 4.2) and $T_{13}$ is the coupling matrix between the supermodes of symmetric section coupler and a single silicon waveguide. The coupling coefficients are calculated according to equation 4.6.

To design a broadband HP coupler, the previously explained model is used as follows:

1. The modes of the symmetric and asymmetric section are computed for a given cross-section and a set of wavelengths (10-20) in the spectral range of interest using Comsol™.

2. The coupling coefficients according to equation 4.6 are calculated.

3. A larger number of lengths for $L_1$, $L_2$, and $L_3$ can be quickly scanned using equation 4.7 to find a solution, where a broadband 3 dB coupling is achieved.

4. The solutions found using the 2D model are confirmed using a full 3D FDTD simulation.

4.4 TM-Mode Broadband Coupling: Simulations

Here, the coupler is designed for the quasi-TM mode of the silicon waveguide. The silicon waveguide cross section is constant throughout the device (340 × 340 nm²). Figures 4.3(a) and (b) show the mode profile of the even (+) and odd (-) TM supermodes of the coupled silicon waveguides at 1.55 μm. The waveguide thickness was chosen due to available wafers at the time.
The power transfer ratio of the directional coupler formed by the silicon waveguides depends on the amplitude and phase of the incident electric field, and the difference in the propagation constants ($\Delta \beta = \beta_+ - \beta_-$) of the coupled modes. This difference in propagation constant is wavelength dependent and thus the power transfer ratio of the silicon coupling section of Fig. 4.2(a) will also be wavelength dependent (shown in Fig. 4.4(a), green line). To compensate, the wavelength dependence of the power transfer ratio an asymmetric HP waveguide section is inserted between the symmetric silicon sections. The HP waveguide will inhibit coupling, because of the large mode difference in both propagation constant and mode profile of the TM silicon waveguide mode on the left and the TM hybrid waveguide mode on the right (see Fig. 4.3(c),(d)). The difference in propagation constant of the non-coupling waveguides will cause a wavelength dependent phase difference between the field coupled to WG B in section 1 and the field still in WG A (see Fig. 4.2). Proper tuning of the lengths of the three sections will allow for a compensation of the wavelength dependence of a simple directional coupler and give rise to broadband coupling.

Depending on the application, different power transfer ratios can be chosen. Here, a design for a 3-dB coupler is presented. To simplify the design process, a simple transfer matrix based design method as described in Section 4.3 is used. The length of three sections as well as the thickness of the silica layer between the silicon and the gold in the hybrid section was varied to achieve broadband power transfer. The final design was simulated using a 3D FDTD simulation to confirm the results obtained from the simplified design process. The material properties of silica, silicon, and gold are taken from [80]. The mesh accuracy and simulation size were varied to ensure convergence and
to estimate the numerical error (See Sec. 2.3). The power at the two output waveguides is calculated by integrating the power density over the cross sections at the end of the waveguides marked by dashed lines in Fig. 4.2(a) by using two power monitors. The final device dimensions for the TM 3 dB coupler design are \( w = 340 \text{ nm} \), \( h_{\text{Si}} = 340 \text{ nm} \), \( h_{\text{spacer}} = 45 \text{ nm} \), \( h_{\text{Ag}} = 200 \text{ nm} \), \( d_{\text{coup}} = 220 \text{ nm} \), \( L_1 = 4.5 \mu\text{m} \), \( L_2 = 3 \mu\text{m} \), and \( L_3 = 0.8 \mu\text{m} \). The power transfer ratio for the final design calculated using a 3D FDTD simulation is shown in Fig. 3 (red line). The power transfer ratio is close to 0.5 (with the value of \( \eta \) limited within the range 0.45 to 0.55) for the wavelength range from 1.45 to 1.6 \( \mu\text{m} \). For comparison the results obtained from the transfer matrix model are also shown (blue line). Both models show good agreement. The slight deviations are caused by reflections between the sections, which were neglected. The deviations could be removed by implementing an eigenmode expansion method (EME) instead of the transfer matrix model [81]. The insertion loss of the coupler is less than 0.2 dB over the entire wavelengths range. Insertion loss is defined as the power loss caused by the directional coupler, when it is inserted between silicon waveguides having the same cross sections (340 nm \( \times \) 340 nm). This loss includes propagation loss caused by presence of metal and reflection loss at the interface of the HP waveguide section with the symmetric dielectric section in the coupler. Since the HP waveguide section is very short, the presence of metal has very little effect on the insertion loss, and the overall insertion loss is negligible.

### 4.4.1 Fabrication Tolerance

Since dielectric waveguide based directional couplers are fabricated using a single etch step, there is no straightforward way to correct for possible variations of the waveguide width from its design value which may occur during fabrication. Fabrication of the proposed device will require etching of silicon, first followed by either thermal oxidation or plasma enhanced chemical vapor deposition (PECVD) for depositing the spacer layer, then followed by a metal deposition and lift off. If after the etching it is found that the silicon waveguide widths are different from the design, the desired power transfer ratio over a broad wavelength range can still be obtained by changing the thickness of the spacer layer.

To illustrate the post-etching correction, the following scenario is considered using FDTD simulations: the spacing between the waveguides \( (d_{\text{coup}}) \) was overetched and changed from 220 nm to 250 nm. As shown by the dashed red line in Fig. 4.5, the device does not work as a 3 dB coupler after such a change. However, as shown by the solid blue line of Fig. 4.5 by changing the spacer thickness to 65 nm and by adjusting...
the section lengths to $L_1=4 \mu m$, $L_2=3.5 \mu m$, $L_3=0.8 \mu m$, $3 \text{ dB}$ operation of the device can be restored. It is important to note that, while the section lengths change, the total length of the device remains $8.3 \mu m$. Dielectric film thickness accuracy within a few nm can be readily achieved using standard fabrication processes, for example, plasma enhanced chemical vapor deposition (PECVD). Although only one possible scenario is considered, the variation of waveguide spacing, the effects of other fabrication imperfections on the coupler performance, e.g., variation of waveguide height ($h_{Si}$) or variations of both waveguide width ($w$) and gap ($d_{coup}$) can also be corrected in a similar manner. The proposed design, therefore, has the additional advantage of being able to compensate for fabrication imperfections, and thus is more robust in terms of fabrication tolerances.

### 4.5 Design and Measurement for the TE-Mode

After designing a broadband coupler for TM, the question was if such a design also exists for the TE polarization. A HP waveguide does not support a plasmonic TE mode, but the metal still has an influence on the mode profile and effective index. Thus, it was possible that a broadband response could still be achieved. The advantage would be that most silicon photonics components for communication applications are based on the TE mode. Additionally, it was decided that a thickness of 220 nm silicon is more common in the community, thus the design was developed with this thickness.

A schematic of the design for the TE polarization is shown in Fig. 4.6. As depicted in the figure, an asymmetric coupling section is created using a HP waveguide on one side, and a standard silicon waveguide is used on the other side (Fig. 4.6(b), right). The asymmetric section is inserted at the end of the coupler for a length $L_2$. In this
Figure 4.6: (a) Topview schematics of the fabricated hybrid plasmonic directional coupler. (b) Crosssectional view of the coupling region, showing the symmetric region at $L_1$ and the asymmetric hybrid plasmonic region at $L_2$. Green color corresponds to silicon, grey to silver and blue to silicon dioxide [82].

Figure 4.7: (a) and (b) are the powerflow profiles of the even and odd modes of the symmetric coupling region ($L_1$). (c) and (d) show the power-flow profiles of the even and odd modes in the asymmetric HP section ($L_2$) [82].
Figure 4.8: The simulated power transfer ratio as a function of wavelength for the proposed and realized HP coupler. The red line is calculated using the simplified 2D model as explained in Sec. 4.3 and the blue line is the simulation result of a 3D FDTD simulation. The green line shows for comparison a standard directional coupler optimized for 50:50 splitting at 1.55 µm [82].

Asymmetric section the coupling between the waveguides is reduced and the propagation constant is changed. The reduced coupling is evident in the mode profiles shown in Fig. 4.7(c,d). In contrast to the symmetric section, where a supermode is formed (see Fig. 4.7(a,b)), the waveguide modes in the asymmetric section are only weakly coupled. Strictly speaking, the TE mode does not have a plasmonic component, but the metal still alters the dispersion and suppresses coupling between the waveguides to allow for the broadband response of our coupler. By tuning the lengths of the symmetric section (\(L_1\)) and the asymmetric section (\(L_2\)), a flat top response of the power transfer ratio can be realized.

The waveguides considered in the simulation and fabrication of the coupler have a height (\(h_{Si}\)) of 220 nm and a width (\(w\)) of 450 nm. The spacing between the waveguides (\(d_{coup}\)) in the final design is 200 nm. The HP coupler has a short total device length of 22.6 \(\mu\)m, where \(L_1\) is 11.4 \(\mu\)m and \(L_2\) is 11.2 \(\mu\)m. The spacer between the silver layer and silicon waveguide (\(h_{Spacer}\)) has a thickness of 70 nm, while the silver (\(h_{Ag}\)) itself is 100 nm thick.

The HP coupler response was optimized using a 2D method, as previously explained in section 4.3, and then the results were confirmed by a commercial 3D FDTD tool [62]. The simulated power transfer ratio of the design is plotted in Fig. 4.8. Both the faster 2D and slower 3D simulations are in good agreement. Also the power transfer
ratio stays within 0.45 and 0.55, a deviation of 10% from the optimum, for a spectral bandwidth of more than 170 nm (blue line, Fig. 4.8). Moreover, for comparison, I have also plotted the power transfer ratio of a conventional directional coupler. In contrast to the HP coupler, the $\eta$ for the conventional coupler stays within the 10% deviation region only for a bandwidth of 40 nm (green line in Fig. 4.8). Thus, my proposed HP coupler realizes a 3 dB power splitting over more than four times the spectral bandwidth of a conventional coupler. Lastly, I should add that the waveguide bends, which are at the beginning and the end of the coupler, are neglected in the 2D simulations, while they are included in the 3D FDTD simulations. Simulations of similar designs in 3D, such as the TM design (Sec. 4.4) without a bend showed better agreement between the 2D and 3D models. Thus, I believe the small deviation in Fig. 4.8 between the full 3D simulation and the faster 2D approach is due to the coupling in the bend region. The bend radius (R) used in our design is 5 $\mu$m.

The tolerance of the design to fabrication imperfections was also analyzed. I found that if the spacer thickness is increased by 10 nm, and thus making the spacer 80 nm thick, the power transfer ratio changes by about 10%. Thus, the coupler is tolerant to typical thickness variations encountered in silica depositions. Alignment between different fabrication layers is also often a problem in integrated optics components. This is not a big issue in this design, as the power transfer ratio changes by less than 5% for a lateral offset of 50 nm between the silver strip and the silicon waveguide for the spectral region of interest.

I fabricated the HP coupler using the procedure outlined in Sec. 2.2. An SEM picture of the final device is shown in Fig. 4.9. The alignment between the metal and silicon etch layer is very good, as the silver sits perfectly on the silicon waveguide. There is some metal on the side of the center strip visible; however, this did not have a large effect on the coupler performance, showing the robustness of the coupler. I believe by further optimizing the double lift-off recipe these metal flakes could be avoided.

To improve the sensitivity of the measurements, the HP couplers were characterized by putting two of them together into a Mach-Zehnder Interferometer (MZI) configuration. One of the arms of the MZI was offset by 100 $\mu$m. The extinction ratio of the emerging wavelength spectrum can be used to determine the power transfer ratio as discussed later in this section. The advantage of this approach is that it is independent of variations in the off-chip coupling for the two outputs, and can thus measure the power transfer ratio with a higher accuracy. An optical microscope picture of the fabricated MZI with couplers is shown in Fig. 4.9(b). The offset of one of the MZI arms causes the light to interfere at the two outputs of the MZI constructively and destructively depending on
Figure 4.9: (a) SEM picture of a fabricated hybrid plasmonic broadband coupler, before coating the device with oxide. (b) An optical microscope picture of the Mach-Zehnder interferometer (MZI) that was used to test the coupler response. The top arm of the MZI has an offset in length by 110 µm. The silver is visible as a yellowish stripe on top of the green silicon waveguides [82].
Figure 4.10: Schematic of the linear setup used to characterize the HP broadband coupler. A movable slit is used to measure the two outputs of the MZI independently.

the wavelengths, creating a beating spectrum.

A Thorlabs broadband super luminescent diode (S5FC1005S) is used to characterize the fabricated device, where a polarizer sets the input polarization state to TE. A free-space coupling setup is used to couple the light in and out of the silicon waveguides. To separate the two output waveguides, a movable slit is positioned into the image plane of the output objective, and a camera is used to ensure that the light from only one waveguide at any point in time is collected. An Ando optical spectrum analyzer (AQ6317B) is then used to record the transmitted power spectrum. To account for losses in the experimental setup, as well as coupling and propagation losses of the silicon waveguides themselves, I also fabricated a straight silicon waveguide and measured its transmission spectrum. The silicon waveguide spectrum is subtracted from the HP coupler spectrum to normalize the HP coupler results.

Figure 4.11 shows the normalized transmission from Input 1 to Output 1 and 2 as defined in Fig. 4.11(b) of the MZI with HP couplers. Across both ports between a wavelength of 1460 nm to 1580 nm I achieved an average extinction ratio of more than 20 dB. The peak extinction ratio occurs at a wavelength of 1502 nm from input port 1 to output port 1 reaching 33.7 dB. The average excess loss of the coupler is 0.89 dB across the spectrum of interest, which is comparable to dielectric designs [67]. From simulations I estimate the material loss due to the silver to be only 0.2 dB, thus the additional loss is attributed to roughness of both the metal film and the silicon waveguides. This low loss is of particular interest and shows that HP-based integrated photonic devices can have low loss, similar to their dielectric counterparts, while they are significantly smaller. I should add that the reason for limiting the wavelength range to 120 nm (from 1460 nm to 1580 nm) was because of setup constraints and not the performance of the HP coupler itself.

Using the extinction ratios of the MZI, the power transfer ratio ($\eta$) of the HP coupler...
Figure 4.11: Measured MZI spectral response after calibrating out the setup and coupling losses.

is calculated as follows. For a Mach-Zehnder Interferometer the electric field at one of the outputs is

$$E_1 = \tau^2 e^{i\phi_b} + \kappa^2 e^{i\phi_t}.$$ (4.9)

Here $\tau$ is the straight through and $\kappa$ the cross field coupling coefficient of the coupler [83] and $\phi_{b,t}$ is the phase accumulated of the light propagating in the bottom and top waveguide respectively (compare Fig. 4.10). The intensity of the field is thus

$$I_1 = |\tau^2 + \kappa^2 e^{i\Delta\phi}|^2.$$ (4.10)

Here I replaced the phase $\phi_{b,t}$ by a global phase $\Delta\phi = \phi_t - \phi_b$. The power transfer ratios are just the squares of the field coupling coefficients ($\eta = \tau^2; \ \eta = \kappa^2$), which can be extracted from the minimum intensity

$$I_{\text{min}} = I_1(\Delta\phi = 0) = (\eta - \nu)^2.$$ (4.11)

Using $\nu = 1 - \eta_a$ and the extinction ratio (ER) we can relate the measurements with the power transfer ratios:

$$ER = \frac{1}{I_{\text{min}}} = \frac{1}{(\eta - \nu)^2} \Rightarrow \eta_a = \frac{1}{2} \pm \frac{1}{2\sqrt{ER}},$$ (4.12)

where I used the fact that $\eta + \nu = 1$ and solved the resulting quadratic equation for
Figure 4.12: Deviation of the power transfer ratio from its optimal $\eta=0.5$ as a function of wavelength [82].

$\eta$. Note that both signs ($\pm$) describe physical solutions. This measurement method makes a coupler that over couples (e.g. has $\eta = 0.6$) indistinguishably from one that under couples, e.g. has $\eta = 0.4$. Thus, it is best to plot the absolute deviation from the optimum, which in this case is $\eta = 0.5$.

The extinction ratio of the MZI can be measured with high accuracy, thus Eq. 4.12 can be used to determine the deviation of the power transfer ratios with a high accuracy. A direct measurement of the power transfer ratios would require the output waveguides to be perfectly equal, which in the used fabrication facilities is often not the case.

In Fig. 4.12, the deviation of the power transfer ratio from its optimum (0.5) as a function of wavelength is plotted together with the theoretical predictions. Theory and experiment show reasonable agreement, especially considering the metal on the side of Ag strip as visible in Fig. 4.9(a). The deviation remains below 0.05 in the spectral region of interest (1480 nm 1580 nm), which means that $\eta$ stays within 0.45 to 0.55 for a wavelength range of more than 100 nm. This is a significant improvement compared to a conventional directional coupler. It is also the same as reported for significantly larger adiabatic coupler designs [67].

In summary, in this chapter, I have presented a broadband coupler that uses a HP waveguide to facilitate broadband coupler. The design of a coupler for the TM polarization as well as the developed efficient 2D design process was presented. Then the design, fabrication and experimental results for a 3 dB HP directional coupler operating around 1.55 $\mu$m for the TE mode of a silicon waveguide are given. The device has a footprint of only 23 $\mu$m by 1.5 $\mu$m and is compatible with future silicon photonics circuits.
The coupler shows a large bandwidth of more than 100 nm and a low insertion loss of 0.89 dB. The loss and extinction ratio could be further increased by optimizing the metal deposition recipe.
Chapter 5

Polarization Transparency

As explained in the introduction, to couple light from a fiber to an integrated silicon photonic circuit one needs to ensure polarization insensitivity of the integrated circuit [57]. Due to the large sensitivity to dimensional parameters such as width and thickness, it has been considered too costly to fabricate truly polarization independent silicon nanowires and devices.

In this chapter I first discuss the current widely accepted approach of polarization diversity. Then, an alternative approach, polarization transparency, is proposed and discussed. The polarization transparency system acts as a polarization adapter, matching the incoming random polarization of the fiber to the TE mode of the silicon waveguide. In Sec. 5.3 it is theoretically proven that the proposed system will convert any polarization to the TE-mode. Then the designs of the integral components of the proposed system are presented. Using these components a first (passive) proof-of-principle was performed (Sec. 5.5). Then, the experimental results of the full polarization adapter are presented. Lastly, a short conclusion is provided.

Originally this was work was planned as an extension of the HP devices presented in the previous two chapters and was meant to include these components (the broadband coupler and the polarization rotator). Instead the proposed system is realized with purely dielectric devices. A system of HP components was considered too risky due to the low yield of these components at the current state. Additionally, the samples in this chapter were fabricated externally for high yield and had to be compatible with the offered fabrication steps.

While I independently worked on this project, some of the concepts for a polarization adapter, such as the idea of linear optical components using a Mach-Zehnder interferometer was published by Miller [84]. Additionally, just before finishing this project an earlier work was discovered, which has some similarities to this work [85].
5.1 (Passive) Polarization Diversity

To solve the need for polarization insensitivity a polarization diversity scheme has been suggested previously [30, 86]. This principle is summarized in Fig. 5.1 using a grating coupled approach (a) and an edge coupled approach (b). In an edge coupled approach (see Fig. 5.1(b)), the incoming light from the fiber is coupled to the TE and TM-mode of the silicon waveguide. The light is then split into two waveguides using a polarization splitter, thus each polarization is coupled to a different waveguide. A polarization rotator in the waveguide with the TM polarization then rotates this TM-mode to the TE-mode. Two identical photonic circuits (one at each waveguide) are used to e.g. encode or decode information. Finally, the original TE mode is rotated to a TM mode and both are coupled back together and off the chip. Thus, a polarization rotator and a splitter are required for the proper operation of the edge coupled polarization diversity system. In the grating coupled polarization diversity approach, a 2D grating coupler converts the two incoming polarizations into two spatially separated modes of the same polarization (usually TE), otherwise the grating coupled approach is the same as for the edge coupled one. Thus the 2D grating acts as a polarization splitter and a rotator at the same time in the grating coupled polarization diversity approach.

It is important to note that the polarization diversity schemes discussed above doubles the required real estate and the power consumed by the chip due to the need of two identical photonic circuits. To overcome this difficulty, it has been suggested [87] to use the same circuit twice by propagating through it in both directions. While this approach can work for simple passive circuits or direct power detection, it will be problematic for more complicated active circuits, such as modulators.

5.2 Active Polarization Transparency

A more elegant solution to the polarization mismatch problem would be to ensure that the random polarization from the fiber could be efficiently coupled to only the TE mode of a single waveguide. The light could then be modulated, multiplexed, or just measured in a single optical circuit, instead of two circuits. Such an polarization adapter would require an active compensation to cope with changes of the incoming polarization state due to temperature and strain fluctuations in the fiber. However, the power and space required for the active compensations is more than offset by the fact that only one optical circuits is required afterwards in contrast to the two optical circuits required in the polarization diversity approach. Thus, a polarization adapter would be advantageous for any larger
active circuit, because only one optical circuit is needed. An polarization adapter could also be used for many more applications, such as: advanced modulation schemes to encode information using the polarization state, quantum key distribution systems, and sensing applications. The polarization adapter could also be used in reverse, where it is possible to create an arbitrary output polarization state for sensing or other applications. Lastly, the circuit could measure and determine the incoming polarization state, i.e. the Stokes parameter of the incoming light.

The polarization adapter, which I propose, is summarized in Fig. 5.2. A system view is shown in Fig. 5.2a and the device schematic is shown in Fig. 5.2b. The adapter can be used with the light incident from the fiber into the silicon circuit or in reverse, where light is coupled out of circuit into the fiber. It is more intuitive to understand the polarization adapter if the light is coming from the chip and is coupled into a fiber, which corresponds to light traveling from right to left in Fig. 5.2. Light in the TE mode of a silicon nanowire is split between two branches (top and bottom) using a 3 dB coupler. One of the branches has a heater (heater $A$) to change the relative optical phase accumulated between the two arms. A second 3 dB coupler is used to couple the arms back together. The output of the second 3 dB coupler is split again into two branches, where the power splitting ratio between the second two branches is determined by the relative phase difference, controlled by heater $A$. One of the arms again has a heater ($P$), which controls the phase between the two waveguides. Both arms are used as the orthogonal inputs into a 2D grating coupler [88, 87]. The heater $P$ effectively controls the phase between the two polarization states in the fiber and thus can switch between linear and circular polarized light.
5.3 Theoretical Proof of Operation

In the following section the polarization adapter system response will be described mathematically for both directions: light incident from a single silicon waveguide and collected using a fiber (light traveling from right to left in Fig. 5.2); as well as light coupled from a fiber into the circuit (left to right). I will prove that an arbitrary polarization state can be coupled without additional loss from the fiber to the TE mode of a single silicon waveguide (device operated from left to right in Fig. 5.2). As well as the device can generate any arbitrary polarization from a single waveguide TE mode, which can be coupled out and into a fiber using the 2D grating (device operated from right to left in Fig. 5.2).

5.3.1 Waveguide to Fiber Coupling

The mathematical description of the polarization adapter is based on a transfer matrix approach, where more information about transfer matrix can be found in [63]. The complex electric field amplitudes in the two waveguides (refer to Fig. 5.2a) are treated as...
the two elements of a 2-element vector. The 3 dB coupler ($\bar{T}$) and the propagation in the two arms with the phase shifter ($\bar{P}_m$) can be described using the following two matrices:

$$\bar{T} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \quad (5.1)$$

$$\bar{P}_m = \begin{pmatrix} e^{i\phi_m} & 0 \\ 0 & e^{i\phi_{m'}} \end{pmatrix} = e^{i\phi_m} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\Delta\phi_m} \end{pmatrix}. \quad (5.2)$$

Here, $\phi_m = L \cdot \beta$ is the phase accumulated due to the propagation in one of the arms with length $L$ in the section $m = [P, A]$ and $\beta$ is the propagation constant in each section. $\Delta\phi_m = \phi_{m'} - \phi_m$ is the difference in phase between the two arms, which can be induced using a heater or by a difference in propagation lengths.

First, I will describe the case where light is coming from the top waveguide, thus I will use the following normalized input vector:

$$\bar{a}_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \quad (5.3)$$

The output of the complete system can then be calculated by multiplying the matrices from Eq. 5.1 and 5.2 (also refer to Fig. 5.2a):

$$\bar{a}_{end} = \bar{P}_P \cdot \bar{T} \cdot \bar{P}_A \cdot \bar{T} \cdot \bar{a}_0 = e^{i(\phi_A + \phi_P)} \frac{1 + e^{i\Delta\phi_A}}{2} e^{i\Delta\phi_P} \left(1 - e^{i\Delta\phi_A}\right). \quad (5.4)$$

The two parts of the final vector $\bar{a}_{end}$ are the two electric field amplitudes in the two waveguides. The 2D grating coupler then converts the two field amplitudes with the same polarization from two inputs (waveguides) into one output (fiber) with orthogonal polarizations. This two waveguide to orthogonal polarization conversion can be considered a geometrical polarization rotation [85]. The global phase $\phi_A + \phi_P$ can be neglected, while the relative phases ($\Delta\phi_{A,P}$) control the output state from the 2D grating and thus the polarization state.

The output vector $\bar{a}_{end}$ can be analyzed further. Of interest for example could be the
magnitude of the two output polarizations, referred to here as $s$ and $p$.

$$|E_s|^2 = \frac{1}{2} \sqrt{(1 + e^{i\Delta \phi_A})(1 + e^{-i\Delta \phi_A})}$$

$$= \cos^2 \left( \frac{1}{2} \Delta \phi_A \right) \quad (5.5)$$

$$|E_p|^2 = \sin^2 \left( \frac{1}{2} \Delta \phi_A \right). \quad (5.6)$$

As expected, the intensity of the electric fields is controlled by the relative phase difference induced by heater $A$. Thus, by passing a current through heater $A$, the relative power between the two polarizations at the output can be controlled.

To switch between a linear polarization and a circular polarization one also needs to control the relative phase between the s- and p-polarizations. It is clear from Eq. 5.4 that the governing component to induce a phase between the output polarizations is $\Delta \phi_P$, which can be controlled using the heater $P$. The phase shifter in the section $A$ will also introduce a phase between the two output polarizations. But as long as the heater $P$ can be tuned to achieve a full phase shift from 0 to $2\pi$, the additional redundant phase shift from heater $A$ can be compensated for.

In summary, using the proposed polarization adapter system, one can couple light from one waveguide into an arbitrary polarization state off the chip.

5.3.2 Fiber Coupling to Waveguide

All the components used in the proposed system (couplers, waveguides, phase shifters, grating couplers) have a linear response and are Helmholtz reciprocal [89], thus any combination of them will also be reciprocal [89]. By proving that the input of one waveguide can be mapped onto any output polarization state in the fiber, it is thus also proven that light input in any polarization state from the fiber can be coupled to one polarization (TE) in a single waveguide. However, a separate proof for light coming from the fiber to be coupled to a single waveguide provides additional insight. Thus, it is provided in the following section.

An arbitrary input polarization state can be described using a Jones vector [63],

$$\vec{a}_{Pol} = \begin{pmatrix} a_1 e^{i\phi_1} \\ a_2 e^{i\phi_2} \end{pmatrix} \equiv \left( \frac{a}{\sqrt{1 - a^2 e^{i\phi}}} \right); \quad \phi = \phi_2 - \phi_1, \quad (5.7)$$

where, $a, a_1, a_2, \phi, \phi_1, and \phi_2$ are real numbers and $0 \leq a \leq 1$. The vector is normalized, i.e. its amplitude will always be one. Additionally, changing $a$ from 0 to 1 corresponds to
going from the s-polarization to the p-polarization, where global phase is again neglected. The elements of $\mathbf{a}_{Pol}$ are the complex field amplitudes of the vertical and horizontal polarization as described in Ref. \[63\].

The 2D grating coupler transmits the two polarization states into the TE mode of two separate silicon waveguides. The state vector will not be changed by this coupling ($\mathbf{a}_{Pol} = \mathbf{a}_{Grat}$), where an ideal coupler with no differential phase shift is assumed. There will also be an insertion loss in general associated with the coupling, but well designed couplers minimize any difference in coupling for the two polarization components \[90\].

The phase shifter $P$ followed by a 3 dB coupler is located after the grating coupler, which introduces a phase in one of the arms. This phase control will allow the light to be split 50:50 after the 3 dB coupler (in section $A$), independent of the amplitude distribution before the coupler. This splitting is achieved by controlling the phase difference between the polarizations by choosing the phase ($\phi_P$) introduced by the first heater accordingly.

The state vector after the first 3 dB coupler can be calculated as follows

$$
\mathbf{a}_{Coup1} = \mathbf{T} \cdot \mathbf{P}_P \cdot \mathbf{a}_{Grat} = \frac{1}{\sqrt{2}} \left( \begin{array}{c} a + \sqrt{1 - a^2} e^{i(\phi + \phi_P)} \\ a - \sqrt{1 - a^2} e^{i(\phi + \phi_P)} \end{array} \right)
$$

As indicated the phase introduced by the phase shifter $P$ (refer to Fig. 5.2a), $\phi_P$, is chosen such that $\phi + \phi_P \equiv \pm \frac{\pi}{2}, \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}$. In eq. 5.8 the Cartesian representation of the amplitude is rewritten into polar form and the following identities are used,

$$
\begin{align*}
|a + \pm i \sqrt{1 - a^2}| &= \sqrt{a^2 + (1 - a^2)} = 1, \quad \forall a \in [0,1] \\
\arg (a + \pm i \sqrt{1 - a^2}) &\equiv \pm \Phi.
\end{align*}
$$

To stress this result again, independent of the input amplitude distribution, the power distribution after the first 3 dB coupler will be 50:50 by adjusting the phase via the heater $P$. The following phase-shifter (heater $A$) with the second 3 dB coupler will be used to ensure that all the power is coupled into a single output waveguide.

$$
\mathbf{a}_{Out} = \mathbf{T} \cdot \mathbf{P}_A \cdot \mathbf{a}_{Coup1} = \frac{e^{-i\Phi}}{2} \left( e^{i(2\Phi + \phi_A)} + 1 \right) \left( e^{i(2\Phi + \phi_A)} - 1 \right) e^{-i\Phi} \begin{pmatrix} 1 \\ 0 \end{pmatrix}
$$

By tuning the phase shifter $A$ in such way that $2\Phi + \phi_A \equiv 0, \pm 2\pi, \pm 4\pi, \ldots$ the light will
be fully coupled to one waveguide, in this case the top one. Thus,

\[ T_{out} = 1 \] (5.12)

where \( T_{out} \) is the normalized transmitted power in the wanted waveguide. Thus there are no system inherent losses, which is a very important feature of the design. The only insertion losses are the component losses (e.g., the grating coupler) which would arise for any polarization diversity approach as well.

A few limitations of this derivation do however exist:

1. For describing the 3 dB coupler an ideal response was assumed, in reality the coupling coefficients are often not exactly \( \frac{1}{\sqrt{2}} \). Also, the phase was assumed to be equal, whereas a directional coupler has a \( \pi/2 \) phase difference at the output. This phase difference would not change the general results, but change the phases the heaters have to introduce to get the same result. However, in the following designs adiabatic couplers are used, which don’t introduce the phase difference, thus this is not a concern.

2. The two arms of the MZI might be unbalanced in both lengths and loss. A too large imbalance in lengths will reduce the bandwidths of the device, while an imbalance in loss in the second MZI will reduce the performance of the device.

3. The analysis was only performed for a single wavelength. If the polarization state remains unchanged for all wavelengths, the bandwidth limitation will arise due to a non-flat response of the phase shifter. A heating based phase shifter will have a limited bandwidth, as the induced phase shift \( \Delta \phi = \frac{2\pi}{\lambda} L \frac{dn_{eff}}{dT} \Delta T \) is wavelength dependent. Thus, the polarization transparent system will be spectrally limited. Additionally, the polarization state might not be the same for all wavelengths. One can assume, though, that the polarization state will be stable over at least roughly one of the telecommunication bands (~50 nm) [85].

5.4 Required Photonic Devices

In the following section, I will discuss the components required for the system described in the previous section and show how they were designed for optimal performance. The following components are needed to assemble the system:

- **Power monitoring** is performed by coupling the light off the chip by using 1D
grating couplers. The layouts for the 1D grating couplers were taken from the Si-EPIC [91] library and were originally designed by [92].

- **A 2D grating coupler** is needed to couple the light from the optical fiber into the chip. It also acts as a polarization splitter and rotator, where both incoming polarizations are coupled to two spatial modes with the same polarization. The coupler, which I used in my fabricated system was designed by myself.

- **The 3-dB coupler** in the MZI is required to perform the mapping into a single waveguide. Standard directional couplers only have a limited spectral bandwidth [66] and are sensitive to fabrication imperfections, thus I used adiabatic couplers. The design used is a slight improvement of a previously published design [67].

- **For phase tuning** a heater is required. 2D thermal and optical simulations were performed to optimize the waveguide cross-section as discussed in Sec. 5.6.1. Instead of a heater one could also implement a PN diode, which uses the plasma dispersion effect to induce a phase shifter. A diode would increase the switching speed, but increases complexity and required space thus was not used here.

I would like to thank Prof. Chrostowski and his students Yun Wang and Han Yuan for providing the layout files (Graphic Database System: GDS) of their adiabatic coupler and 1D grating coupler designs as well as some of their simulation files.

### 5.4.1 1D Focusing Grating Coupler

A 2D grating coupler consists of two 1D grating couplers overlayed orthogonal to each other. Hence, once the 1D grating coupler is understood, the derivation of the 2D coupler will be more straightforward.

When coupling light from a fiber to a silicon waveguide, one has to ensure phase matching between the fiber mode and silicon waveguide mode. This is usually done using a grating, where the required period can be derived as given below [93]:

\[
n_{\text{eff}} - n_f \cdot \sin \theta = m \frac{\lambda}{\Lambda}.
\]  (5.13)

Here, \(n_{\text{eff}}\) is the effective mode index of the silicon slab mode, \(n_f\) is the effective index of the fiber mode, and \(m\) is an integer corresponding to the grating order. \(\theta\) is the angle the fiber makes to the surface normal of the grating. Lastly, \(\lambda\) is the vacuum wavelength of light and \(\Lambda\) is the pitch of the grating. While a simple grating like this allows for strong coupling into the slab mode of the silicon waveguide, a taper is then required to couple
the light from the wide grating (~10 µm) to a nanowire waveguide (450 nm wide). These adiabatic tapers are typically a few hundred microns long.

To shorten the total length of the grating, one can use a focusing grating coupler. In a focusing grating coupler the grating teeth are bended to form a set of ellipses, which are phase matched to focus the light into a silicon nanowire waveguide instead of using a long taper.

The equation to construct such a grating can be derived as follows, where the distance from the entrance into the nanowire waveguide is \( r \) and angle made with the propagation direction of the waveguide is \( \phi \) (compare Fig. 5.3a). The phase matching is fulfilled for the following case \[88\]

\[
 n_{\text{eff}}kr = n_fkr \sin(\theta)\cos(\phi) + 2\pi N, \tag{5.14}
\]

where \( N \) is an integer and \( k \) is the vacuum light vector \( (k = \frac{2\pi}{\lambda}) \). Solving this equation for \( r \), yields

\[
 r = \frac{NA}{n_{\text{eff}}(1 - \epsilon \cos(\phi))}. \tag{5.15}
\]

Here, \( \epsilon \) is the eccentricity of the ellipse, which is defined as:

\[
 \epsilon = \frac{n_f \sin(\theta)}{n_{\text{eff}}}. \tag{5.16}
\]

A scanning electron microscope (SEM) image of a fabricated focusing grating coupler is shown in Fig. 5.3b.
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5.4.2 2D Polarization Diversity Grating

The 2D grating can now be constructed by overlapping the ellipses equation (previously discussed) at 90° angle. At each intersection point of the two ellipses one places a scattering center, i.e. etches a hole. This is illustrated in Fig. 5.4a.

To ensure high performance the grating coupler was simulated using FDTD Lumerical. The simulated spectrum of the final design is shown in Fig. 5.5(a). The final design was obtained by varying a number of key dimensional parameters. The outcome of these parameter studies and experimental results can be found in Appendix B.

A SEM image of a typical 2D grating coupler which was fabricated is shown in Fig. 5.5(b).

Figure 5.4: (a) Ellipses of two focus points. The red dots are the intersection points at which a scattering center will be placed. (b) A color plot of the effective index of the 2D focusing grating.

Figure 5.5: (a) Simulated Spectrum of the 2D grating coupler. (b) SEM of a fabricated 2D grating Coupler.
5.4.3 50:50 Adiabatic Coupler

A directional coupler is a simple device used to couple light between waveguides. However, directional couplers are typically very sensitive to fabrication imperfections and have a limited bandwidth as discussed in Chapter 4. To ensure good performance independent of fabrication imperfections and a high yield for the polarization transparent system, an adiabatic coupler was used instead of the more sensitive directional coupler.

The reason why the directional coupler is sensitive to imperfections lies in its principle of operation. In a directional coupler both the symmetric and antisymmetric super-mode are exited when launching light in one input. The power is then transferred between the waveguides due to interference between the super-modes, as illustrated in Fig. 5.6(a). The difference in propagation constants will determine the length of the coupler for which the desired power transfer occurs; however this difference is highly sensitive to fabrication imperfections. A 10 nm offset in the width can change the power coupling for a given lengths by up to 40% [66].

In contrast, in an adiabatic coupler each input only excites one of the super modes. This is accomplished by changing the width of the input waveguides: one waveguide gets widened while the other is narrowed. If the offset is large enough, light will not couple between the waveguides and the mode will be confined nearly completely in one waveguide. The modes can now adiabatically transformed into a super-mode with 50:50 power distribution. This mode transformation is achieved, by equalizing the width of the waveguides while they are already in close proximity. This causes the modes to change their mode profile to an even distribution between the two waveguides. The evolution of the modes is illustrated in Fig. 5.6(b).

A schematic diagram, which gives the final dimensions, is given in Fig. 5.7. The
dimensions were varied to have optimal performance while keeping the device length small. The different optimization and plot of the results can be found in Appendix C. The final values used in the simulation are given in Table 5.1. The final result gave a 50:50 coupling for a more than 120 nm spectral bandwidth, which was more than sufficient.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{Input}}$</td>
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<td>µm</td>
</tr>
<tr>
<td>$L_{\text{Taper}}$</td>
<td>50</td>
<td>µm</td>
</tr>
<tr>
<td>$L_{\text{Coupler}}$</td>
<td>155</td>
<td>µm</td>
</tr>
<tr>
<td>$L_{\text{Sbend}}$</td>
<td>15</td>
<td>µm</td>
</tr>
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</tr>
<tr>
<td>$w_2$</td>
<td>650</td>
<td>nm</td>
</tr>
</tbody>
</table>

5.5 Proof of Principle: one Heater

As a first proof of principle experiment, I designed a system that does not require fabricated on-chip heaters, but can be tuned by changing the sample temperature. However, as the temperature can only be tuned for the whole sample, only either the phase or the power distribution between the two polarizations can be changed. Thus, this system will be able to couple all the light of a fiber into one waveguide but only for a specific subset of polarizations.

The GDS layout of the system is shown in Fig. 5.8a. Red regions are protected areas during the first etch resulting in a layer of 220 nm silicon. Yellow areas are used for the second etch, which is a partial etch of 70 nm; this partial etch results in a silicon thickness of 150 nm. A fiber array with a 127 µm spacing between the fibers will be aligned to the three grating couplers at the bottom. Light can be sent into the 2D grating coupler on the very left. The light is then split into the to the TE mode of the
Figure 5.8: (a) Computer screenshot of the gds layout of the fabricated proof of principle devices. (b) An optical micro graph of the fabricated system.
two waveguides. The orientation of the light polarization decides into which waveguide how much light gets coupled. The two outputs of the 2D grating coupler are connected to an adiabatic coupler, which mixes the light of the two arms of the grating coupler. A second adiabatic coupler is located after the first in the GDS underneath the first one. The waveguides between the two adiabatic couplers have different lengths, which causes a wavelength dependent phase shift between the two arms. The sample stage temperature is controlled and thus used to change the phase shift. The output of the system is accessed using two 1D grating couplers. The unbalanced MZI had an offset in length of 70 \( \mu \text{m} \), where the offset is visible in the difference in waveguide lengths between the two adiabatic couplers in the top right.

The 2D grating couplers were designed by overlapping a number of focusing ellipses at an orthogonal angle and placing scattering centers at the intersections similar to [88]. The 1D grating couplers are based on a previous design [92] and the adiabatic couplers are a slight improvement of a previous design by Han Yun [67].

The samples were fabricated using e-beam lithography, which first wrote the full etch pattern into resist. The pattern was then transfered using reactive ion etching. The partial etch pattern was done similarly afterwards. The resulting structure with a top oxide cladding is shown in Fig. 5.8b.

For the sample characterization light from an Agilent tuneable laser with a wavelength range from 1.48 \( \mu \text{m} \) to 1.59 \( \mu \text{m} \) and 1 mW of power is coupled into a polarization-maintaining fiber (PMF) and coupled onto the chip using a fiber array. The fiber array consists of 8 PMF fibers in a line with a spacing of 127 \( \mu \text{m} \). One fiber is used as an input and connected to the laser, while the other fibers are connected to power meters to measure the transmitted power. This set spacing allows for a fast alignment between the fibers and grating couplers on chip and combined with an automated setup allows for linear transmission data of thousands of devices in mere hours [95, 96].

To first demonstrate the switching between output ports we measured the transmission spectrum of our system. The normalized transmission is shown in Fig. 5.9b. The light was incident on the 2D grating coupler and had the electric field polarized horizontally with respect to Fig. 5.8b. Due to the unbalanced MZI the light switches between the two outputs as a function of wavelengths. The spectrum shown here can be spectrally shifted by changing the sample temperature. Additionally, while not shown here, other polarization states would show a similar spectrum only spectrally shifted. Due to small process variations the output spectrum is not perfectly identical between the two ports. For example the 1D grating couplers have slightly different loss.
Figure 5.9: (a) Automated measurement setup at UBC used for the experiments [94]. (b) Normalized transmission spectrum of the device shown in Fig. 5.8b. The light is injected into the 2D grating coupler and the transmission at the two 1D grating couplers (Port 1 & 2) is measured. Due to the offset in the MZI a beating pattern as function of wavelength is observed.
5.5.1 Experimental Polarization Switching

In our first experiment light was sent through the input fiber aligned with one of the 1D grating couplers as indicated in Fig. 5.10a. The light going through the system was coupled out through the 2D grating coupler into a fiber. A collimator focused the light into free space and a polarization beam splitter separated the light into its two orthogonal polarized components. The two components are defined as follows: The light is polarized either along the slow axis or the fast axis of the polarization maintaining fiber. The power in the two components as a function of sample temperature is plotted in Fig. 5.10b. The power switches between the two polarizations as the temperature increases. This switching is the direct result of the change in phase shift in the unbalanced MZI, which then leads to a change in output power distribution. These results were obtained at a wavelength of 1.55 $\mu$m. Other wavelengths showed similar behavior with a temperature shift for maximum transmission of a specific polarization state.

5.5.2 Polarization Independent Coupling

A schematic of the next experiment is shown in Fig. 5.11. Light from an Agilent tunable laser source is coupled to free-space and send through a polarizer, a half-wave plate, and lastly a quarter wave-plate. The wave-plates are used to get full control over the polarization state of light. The light is then focused back into a polarization maintaining fiber and coupled to the 2D grating coupler on the chip. The output of the polarization transparency circuit is monitored by coupling the light off the chip using two 1D grating couplers designed for the TE mode of a silicon waveguide.

I measured the insertion loss of the setup and fiber to coupler first. The 2D grating coupler had an insertion loss of 13 dB, the 1D grating coupler had a coupling loss of 8.3 dB, and the free space coupling setup had a loss of 9.2 dB. The loss of the grating couplers was higher than previous results [92, 88] as the 2D grating coupler and 1D grating coupler were accidentally designed for different angles, thus light was coupled from the fiber to the grating coupler at a suboptimal angle for both gratings, as the fibers can not be aligned separately. I then subtracted the insertion losses of the components from our polarization coupling results.

Here, I demonstrate that a number of different polarization states can all be coupled to the same output waveguide. The system was tuned again by changing the stage temperature and thus tuning the phase difference in the MZI located between the couplers. This MZI controls the power distribution between the two output polarization states. Due to the heat capacity of the whole stage it can take a few minutes to reach a specific
Figure 5.10: (a) Schematic representation of the first proof of principle measurement. In this case the tuning of the polarization was demonstrated. (b) Normalized transmission of the system with light incident on one 1D grating coupler and coupled off through the 2D grating coupler. As the sample is heated light is switched between light polarized along the fast axis of the polarization maintaining fiber and light polarized along the slow axis.
Figure 5.11: Schematic representation of the second proof of principle measurement. Successful coupling of different linear polarization to one output with high extinction was demonstrated.

temperature. Thus, to allow for fast data acquisition, we would set the stage temperature to $T_1$ and then tune the wave-plates to find the polarization state that couples optimally. I would record the angles of the two wave-plates and then change the stage temperature to $T_2$ and repeat the previous procedure. This process was faster than preselecting the polarization state and then finding the matching temperature. A schematic of the setup is shown in Fig. 5.11.

The polarization orientation angle that means the power distribution between the fast and slow mode in the polarization maintaining fiber can be calculated using the Jones matrix approach. In this case the angle of interest is the polarization orientation angle $\Psi$, the angle between the major axis of the polarization ellipse with the fast axis of the polarization maintaining fiber. The polarization angle was calculated using the recorded angles of the wave-plates which is explained in Ref. [83]. Also later in this chapter $\Psi$ is explained in more detail and its relation with the Stokes parameter is given (see Sec. 5.6.2).

The experimental results of coupling a variety of polarization states to the silicon photonics circuit are shown in Fig. 5.12. The power was always coupled to Output 1 for all polarization states which had an orientation angle ranging between from nearly zero radian and all the way up to $\pi/2$. Output 2 was suppressed with an extinction of more than 31 dB. Output 1 had an average insertion loss of 0.07 dB, after accounting for external factors as discussed previously, with a standard deviation of 0.62 dB. The upper and lower bounds were 1.1 dB and -1.3 dB. Hence, the maximum variation of the output 1 is only 2.4 dB. This variation can be explained by thermal drifts in alignment of the free space coupling setup as well as the fiber to chip setup.
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Figure 5.12: Normalized transmission of the proof of concept polarization transparency system as a function of input polarization angle ($\psi$). More than 25 polarization states were all coupled to one polarization in one waveguide.

In summary in this first proof of principle experiment I successfully coupled more than 20 polarization states to a silicon photonics circuit. The light was collected in the TE mode of a single waveguide with less than 2.4 dB variation and a system loss of only 0.07 dB.

5.6 Full Control: Two Heaters

For the full system two heaters were required to control the two phase shifters independently. The passive functionality of this system, meaning the silicon waveguides, was fabricated at the IMEC facilities in Belgium accessed through CMC Microsystems. There, a SOI wafer was patterned using UV lithography and the top silicon layer was etched. This process was repeated to provide both a full etch of the 220 nm silicon as well as a partial etch of 70 nm resulting in a silicon thickness of 150 nm. Plasma enhanced chemical vapor deposition deposited a silica cover layer of 2 $\mu$m. These samples were then distributed to me and I deposited tungsten at our local fabrication facility on top of the silica. The tungsten was positioned above the waveguides to allow for thermal tuning. The details of the heater performance are explained in the next subsection followed by the optical experimental results. The GDS layout of the fabricated system is shown in Fig. 5.13b(a), while an optical microscope picture of the fabricated device is shown in
5.6.1 Phase Tuning

A phase change between the two waveguides in an MZI is required for operation of the active polarization transparency. The most common approach is to use electrical heaters \[97\] to change the real part of the effective index of the silicon waveguide through the thermo optic coefficient of silicon. By passing an electrical current through a small wire, the metal wire itself and its surrounding are heated. If the wire is located close enough to a silicon waveguide, the induced temperature change of the waveguide will change the refractive index of the silicon and silica and thus change the effective index of the waveguide.

The heaters in my proposed polarization system were fabricated by myself in the Toronto Nanofabrication Facility (TNFC) of the University of Toronto. To predict performance of the heater the optical and thermal response were simulated in Comsol Multiphysics \[64\]. Here two device dimensions are of interest; How close can the heater be located to the waveguide to induce a large temperature swing, while not inducing metal losses to the propagating light? Additionally, during the design it might be possible that a second waveguide needs to be located close to the heated waveguide, such as the other arm of the MZI. The thermal cross talk between the waveguides needs to be minimized, as smaller thermal cross-talk increases the induced phase difference and stability of the system.

A cross section of two silicon waveguide with one heater on the top is shown in Fig. 5.14. Here the heating is simulated by introducing the dissipation of a given power at the heater and then the induced temperature change at the two waveguide is monitored. The simulation is based on a finite element method solver (COMSOL) of the steady state heat equation,

\[
- k(\Delta T) = Q. \tag{5.17}
\]

Here \(k\) is the thermal conductivity (silicon: 130 \(W \cdot m^{-1} \cdot K^{-1}\); silica: 1.38 \(W \cdot m^{-1} \cdot K^{-1}\)) , \(T\) the local temperature, and \(Q\) the heat dissipated by the heater in \(W \cdot m^{-3}\). The boundary condition chosen for the simulation was a constant temperature of 20 °C.

A large temperature increase at the waveguide beneath the heater is wanted for larger refractive index changes, while the temperature at the waveguide on the side should remain constant to reduce crosstalk. The distance between the waveguides was 10 \(\mu m\).

The induced propagation loss due to the metal is shown in Fig. 5.15(a). These simulations are based on optical mode simulations where the complex refractive index of Ni was
Figure 5.13: (a) Screenshot of the GDS layout of the full system. (b) An optical micro graph of the fabricated system.
used. Thus the propagation loss is purely the loss induced by to metal. The qualitative results are independent of the choice of metal. The plot gives the loss in dB/mm as a function of spacer thickness between the waveguide and the metal. The loss is less than 1 dB/mm for a thickness of 800 nm. The MZI will only have a length of about 100 µm and thus the loss due to the metal for this thickness would be about 0.1 dB, which is a more than acceptable value. To account for the variations in fabrication and metal losses due to the choice of metal the final thickness chosen was 1 µm.

The induced temperature change between the two waveguides of Fig. 5.14 is shown in Fig. 5.15(b) for two spacer thicknesses as a function of dissipated power per µm. The final power required for the heater will depend on the lengths of the heater used.

To ensure that it is possible to dissipate the needed power without damaging the heaters, a few test stripes of tungsten with a thickness of 300 nm and width ranging between 4 and 7 µm were deposited. The current-induced breakdown of the metal stripe occurred around 1 mW per µm which is higher than needed for my design.

To summarize, in this section I have described a number of mode and thermal simulations to design the heaters required for the polarization system. A spacer thickness of more than 1 µm will ensure low loss operation.

5.6.2 Full Polarization Adapter

The samples of the full polarization adapter fabricated at IMEC with tungsten heaters deposited in Toronto were then characterized. The characterization was done at the Laval University in the lab of Prof. Wei Shi in a setup similar to the one at UBC (See Fig. 5.9a). In the first experiment a number of polarization states were successfully coupled to the
system with all the light always collected in the TE mode of one waveguide. A schematic of this setup is shown in Fig. 5.16. The polarization states were created by coupling the light from an Agilent 81600B laser to free space and sending the light through a $\lambda/2$ and a $\lambda/4$ wave-plate.

Before performing the experiment I calculated the polarization states one can create using the two ($\lambda/2$ and $\lambda/4$) wave-plates. The results are plotted in Fig. 5.17 in the Poincaré sphere. For this plot the two wave plates each had every possible combination of 0° to 90° to the x-axis with a step of 10°. The plot proves that going through these angles fully covers the Poincaré sphere, thus when the wave plates are rotated from 0° to 90° independently all polarization states that exist are covered.

In the Poincaré sphere, the polarization states are described using the four Stokes parameters. The polarization of the light is then plotted using the $S_1$, $S_2$, and $S_3$ parameters representing the three Cartesian axes. Alternatively one can use a spherical coordinate system as well. In a spherical coordinate system, the angle of the polarization state in the Poincaré sphere makes with the $S_1$ axis is referred to as $2\Psi$ (see Fig. 5.18a) which is the angle the major axis of the polarization ellipses makes with x-Axis. While the angle with $S_1$ and $S_2$ plane is called $2\chi$ and is the opening of the polarization ellipses, thus indicates how linear or circular the polarization of the light is. Figure 5.18b shows the polarization ellipse for an elliptically polarized wave with $\Psi$ and $\chi$ indicated. In the following experiment the results will be presented as a function of these two angles. In general $\Psi$ is between $[-\pi/2, \pi/2]$ and $\chi$ is $[-\pi/4, \pi/4]$. This set of angles covers the full Poincaré sphere.
Figure 5.16: Schematic representation of the final polarization transparency experiment. Here the light is inserted into the 2D grating coupler and collected at the 1D couplers. Successful coupling of any polarization to one output with high extinction was demonstrated.

Figure 5.17: A Poincaré sphere (grey), with the to be created polarization states indicated by blue markers.
The goal of the first experiment was to show that the light incident onto the polarization adapter can be coupled to the TE mode of one silicon waveguide, independent of the light’s polarization state. To demonstrate this, a polarization state was created using the two wave-plates and coupled back into a polarization maintaining fiber which was aligned with the 2D grating coupler of the polarization adapter. Two other fibers were aligned with the 1D grating couplers and the amount of light exiting the 1D grating couplers was recorded, thereby monitoring the light in the two silicon waveguides. Currents were then applied to the two heaters of the integrated silicon photonics circuit in such a way that the light at waveguide 1 was maximized, minimizing the output at waveguide 2. A correct operation of the polarization adapter will make it possible to have only a small variation in light power in waveguide 1, while there should be only negligible light power in waveguide 2.

The recorded optical power normalized by the average as a function of the polarization angles $\Psi$ and $\chi$ is plotted in Fig. 5.19a. Polarization states with $\Psi$ between $[-\pi/2, \pi/2]$ and $\chi$ between $[-\pi/4, \pi/4]$ were created. This set of angles spans the full spectrum of polarization states such as: linear, circular, TE, TM, and anything in between. For each state the light at the wanted waveguide 1 was measured and in the end normalized to the average insertion loss. As evident in Fig. 5.19a the power varies for different polarization states, but stays between $\pm 1$ dB of the average with a standard deviation of $\pm 0.56$ dB. These results were obtained at a wavelength of 1.55 $\mu$m.

The average insertion loss was 25 dB. The loss was distributed as follows: the free
Figure 5.19: (a) The deviation from the average insertion loss recorded at the wanted output waveguide 1 for different polarization states in dB. The results are color-coded, a black point has an average insertion loss. The more blue a point is the less insertion loss (positive dB) was recorded, while more red indicated larger insertion loss (negative dB) (b) The extinction ratio recorded at the unwanted output waveguide 2 for different polarization states. The results are color-coded. A yellow point had the smallest insertion loss, while the darker the point is the larger was the extinction ratio.
space coupling setup had a coupling loss of 6.2 dB; the 1D grating coupler contributed with about 8 dB; while the 2D grating coupler caused the remaining 11 dB. While these losses are high, the 1D and 2D grating coupler designs are not state of the art and could be improved.

The incident power at the unwanted waveguide 2 was also recorded. The resulting extinction ratios $\frac{P_{Wg_2}}{P_{Wg_1}}$ are plotted in Fig. 5.19b for the same polarization states as in Fig. 5.19a. The extinction ratio always stays above 30.9 dB, while an average extinction ratio of 36 dB was obtained.

In summary, these results prove that it is possible to couple any polarization state to the TE mode of a single waveguide, thus enabling an adapter between the constantly changing polarization in a fiber to the required polarization state of a silicon photonics circuit in a stable fashion.

### 5.6.3 Polarization Analysis

When looking at Eq. 5.11 one notices that the required phase to be induced by the heater $A$ is directly dependent on the power distribution between the TE and TM mode and thus should be correlated with $\Psi$. If the heater is characterized and a relationship between the voltage applied at the heater and the phase induced by the heater is known, one could measure $\Psi$ just by knowing the voltage applied at the corresponding heater.

Figure 5.20 shows $\Psi$ versus the applied heater power for the polarization transparency.
Figure 5.21: Schematic representation of the final polarization creation experiment. The arrow indicates the flow of light. Here the light is inserted into the 1D grating coupler and collected at the 2D coupler.

results obtained in Sec. 5.6.2 There is a linear relationship visible between $\Psi$ of the incident state and the power required to achieve transparency. However, some states have a deviation in $\Psi$ of $\pm \pi/4$ with respect to the linear fit. This means from the heater power alone, one might predict the polarization to be 45° polarized while the state actually is TE or TM. Thus, to use the system as a polarization analyzer further improvement of the stability of the system is required.

The most likely cause of this deviation is the missing of a temperature controlled stage for the sample. As the system would be tuned to polarization transparency for a specific polarization the top of the chip can reach temperatures of 100 °C. This causes the whole sample to slowly heat up and thus change the induced phase difference between the two waveguides. The phase change was observable in a drop of the extinction ratio within half a minute after alignment to a specific polarization. The use of a temperature controlled stage would reduce this problem and allow the polarization adapter to work well as a polarization analyzer.

### 5.6.4 Polarization State Creator

Lastly the same integrated silicon photonics system was used to create a number of polarization sates. For this light from the same Agilent laser system was coupled into one of the 1D grating couplers. The light from the 2D grating coupler was then collected using a polarization maintaining fiber and analyzed in free space. To analyze the output polarization state the transmission through a linear polarizer was recorded. The polarizer
was set at $0^\circ$, $45^\circ$, and $90^\circ$. Additionally, a data point was taken with the polarizer set at $45^\circ$ and a $\lambda/4$ wave plate inserted before the polarizer with the fast axis also at $45^\circ$.

The resulting intensities through the polarizer can be used to calculate the Stokes parameters and thus the polarization angles $\Psi$ and $\chi$ according to [99]

\begin{align*}
S_0 &= I(0,0) + I(90,0), \\
S_1 &= I(0,0) - I(90,0), \\
S_2 &= 2 \cdot I(45,0) - I(0,0) - I(90,0), \\
S_3 &= 2 \cdot I(45,45) - I(0,0) - I(90,0), \\
\Psi &= \arctan \left( \frac{S_2}{S_1} \right), \\
\chi &= \arctan \left( \frac{S_3}{\sqrt{S_1^2 + S_2^2}} \right).
\end{align*}

Here, $I(a, b)$ is the recorded intensity with the polarizer set at an angle $a$ and the wave plate not inserted ($b = 0$) or set at $45^\circ$ ($b = 45$).

To create a number of polarization states different voltages were applied to the integrated heaters and the transmission was measured. The results are plotted in Fig. 5.22. First the heater $P$ was set to a specific power, then the heater $A$ was continuously tuned.
The results show four different powers set at heater $P$ and the shifts of the polarization states as the power at heater $A$ was changed. Polarization states ranging from linearly polarized light, with the electric field pointing in different direction, through elliptical states to circularly polarizations are achieved.

### 5.7 Conclusion

In summary, in this chapter I have proposed a polarization adapter to overcome the polarization mismatch between an optical fiber and an integrated photonic circuit. The system and its component were designed. The systems principle of operation was also theoretically analyzed to prove it will work for all polarization sates. Then, a simplified system with only one phase tuner was successfully measured. Lastly, the full system with integrated heaters was characterized. It was shown that any polarization from an optical fiber can be coupled to the TE mode of a single silicon waveguide with a light power deviation in the waveguide of less than $\pm 0.56 \text{ dB}$ across all possible input polarizations.
Chapter 6

Conclusion

6.1 Summary of Work

Silicon photonics has been a very active area for photonic research in the past years and this interest is likely to continue. Integrated photonic circuits in silicon have the prospect to solve the interconnect problem in a computer chip and provide access to faster computational speeds. Furthermore, silicon photonics has much prospect in the area of biosensing to implement the lab-on-a-chip in an integrated photonics circuit. In order to make these applications possible, the coupling of light from a fiber to photonic circuits should be stable and should have low loss. Additionally, in order to manipulate light on the chip, several components need to exist.

The objective of this thesis was to find a practical solution for polarization control in a silicon photonics circuit. Polarization control is needed for a number of issues in addition to sensing applications, primarily to solve the problem of polarization mismatch problem between the silicon photonics circuit and an optical fiber. It was successfully demonstrated that a polarization adapter system can be realized in a silicon photonics circuit. Additionally, a new ultra-compact polarization rotator and broadband coupler were demonstrated, both of which took advantage of the unique abilities of hybrid plasmonic waveguides. These devices can be used in future polarization adapter systems as discussed below.

6.2 Future Directions

A number of future directions are possible for the presented work.

Further improvements can be applied to the separate components of the polarization
adapter system as it has been demonstrated. The 2D grating coupler performance is rather low, and the goal should be to get insertion losses closer to 1 dB. Other groups have proposed promising designs that reach this level and that could be implemented. For the 1D grating coupler, comparable losses have already been demonstrated. Thus, combining these two coupler, would significantly reduce the insertion loss of the system from currently $\geq 15$ dB to $\sim 2$ dB. The implemented heater system could also be further improved and balanced with respect to waveguide loss in the mach-zehnder interferometer.

To make the polarization adapter fully integrated, a feedback system should be implemented. The input of the system could be an integrated germanium photo-diode placed on one of the waveguide outputs. The electronic feedback system should then be programmed to reduce the amount of light coupled into this waveguide as much as possible. While there is only one input (one photo-diode), but at least two outputs (two heaters), the system could be programmed in such a way that it changes which output it controls every few microseconds (the switching time is just an example and should be optimized). Thus, it first optimizes the heater $A$, then heater $P$, and then alternates between the two heaters.

In order to further investigate the stability of the system, a number of experiments can be done. For example, it can be confirmed that the system will stabilize to a polarization change on time. In that case, the polarization can be changed by e.g. moving a fiber around for instance, while an automatic system stabilizes the coupling and the power in the desired waveguide is monitored.

There have also been demonstrations of a polarization control system using a silicon photonics circuit where the light was edge coupled to the circuit instead of using a grating coupler. To use this system in a similar fashion to the system realized here, one needs a polarization splitter/rotator component. In previous demonstrations dielectric designs were used. While these showed good performance, they were also extraordinarily large (more than 200 $\mu$m long). One option is to use the realized HP rotator and a HP polarization splitters realized by other groups to fabricate an ultra-compact, edge coupled polarization control system.

Further research is also warranted into the possibility of fabricating of HP components using standard CMOS technology. Most likely this would involve replacing the silver used here with a more lossy metal, but one that can withstand the high temperature process typically used in CMOS manufacturing.


6.3 Resulting Publications

6.3.1 Journal Publications


6.3.2 Conference Contributions


Appendix A

Fabrication Recipes

A.1 Alignment Makers

1. Clean samples
   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
   (d) 10 s blow-dry

2. Spin coat MMA-El 11 for 45s with max. speed 2000 rpm and 584 acc

3. Bake resist on hotplate for 2 mins at 180°C

4. Spin-coat PMMMA for 45s with max. speed 2000 rpm

5. Bake resist on hotplate for 2 mins at 180°C

6. Mount sample on e-beam holder and expose pattern (Fracture Resolution 25 nm)

7. Develop Samples
   (a) 70 s in MIBK:IPA, 1:3
   (b) 30 s IPA
   (c) 15 s blowdry

8. Deposit tungsten in sputterer
9. Lift-off in Acetone, 5 mins soaking, 5 mins ultrasonic bath (—if markers lift-off here, they won’t survive the rest of the procedure, thus better to lose them here then later.)

10. Rinse with IPA

A.2 Silicon Waveguide Etching

1. Clean samples

   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
   (d) 10 s blow-dry

2. Spin coat ZEP 520A for 60s with max. speed 6000 rpm and 584 acc

3. Bake resist on hotplate for 3 mins at 180°C

4. Mount sample on e-beam holder and expose pattern (Fracture Resolution 10 nm, Dose 240 μC/cm²)

5. Develop Samples

   (a) 60 s in ZEDN50
   (b) 30 s IPA
   (c) 15 s blowdry

6. Etch waveguides in reactive ion etcher (Phantom) with 80 W RIE, 80 mT, 25 scm SF₆, 12 scm O₂, 10 scm He, 5 mT He, for 56 seconds.

7. Remove resist with ZDMAC, 10 min ultrasonic bath

8. Rinse with distilled water

9. Clean in IPA, 1 min ultrasonic bath
A.3 Deposit Silica Spacer

1. Clean samples
   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
   (d) 10 s blow-dry

2. Load sample into PECVD and use 3.8 nm/min SiO2 recipe for 11 mins (→ gives ∼70 nm silica)

A.4 Metal Deposition and Lift-Off

1. Clean samples
   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
   (d) 10 s blow-dry

2. Spin coat MMA-El 11 for 45s with max. speed 2000 rpm and 584 acc

3. Bake resist on hotplate for 2 mins at 180°C

4. Spin-coat PMMMA for 45s with max. speed 2000 rpm

5. Bake resist on hotplate for 2 mins at 180°C

6. Mount sample on e-beam holder and expose pattern (Fracture Resolution 2.5 nm, Dose ≥900 µC/cm²)

7. Develop Samples
   (a) 70 s in MIBK:IPA, 1:3
   (b) 30 s IPA
   (c) 15 s blowdry

8. Deposit Metal
(a) Check distances, sample: x=0 cm, y=3 cm, z=20 cm; height monitor: x=11 cm, y=1.5 cm, z=11 cm; Use tooling factor of 0.84

(b) Before deposition keep shutter closed and activate e-beam current with current at least as large as planned maximum current and ensure that vacuum remains, keep at large current for 30 seconds after vacuum stabilized.

(c) Deposit \( \sim 2 \) nm of Chromium with a current of 14 mA

(d) Deposit silver as needed, start current \( \sim 25 \) mA, to deposit first 10 nm, then increase slowly to up to 45 mA to deposit remaining silver

9. Lift-off in Acetone, 5 mins soaking, 1 mins ultrasonic bath

10. Rinse with IPA

### A.5 Silica Top Cladding

1. Clean samples
   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
   (d) 10 s blow-dry

2. Spin coat FOx-15 for 60s with max. speed 2000 rpm and 584 acc

3. Bake on hotplate for 10 mins at 110°C

4. Spin coat FOx-15 for 60s with max. speed 2000 rpm and 584 acc

5. Bake on hotplate for 20 mins at 110°C

### A.6 Heater deposition

1. Clean samples
   (a) 5 min ultrasonic bath in acetone
   (b) 10 s blow-dry, clean glassware with IPA
   (c) 5 min ultrasonic bath in IPA
Appendix A. Fabrication Recipes

(d) 10 s blow-dry

2. Spin coat MMA-El 11 for 45s with max. speed 2000 rpm and 584 acc

3. Bake resist on hotplate for 2 mins at 180°C

4. Spin-coat PMMMA for 45s with max. speed 2000 rpm

5. Bake resist on hotplate for 2 mins at 180°C

6. Mount sample on e-beam holder and expose squares for alignment

7. Develop Samples
   (a) 70 s in MIBK:IPA, 1:3
   (b) 30 s IPA
   (c) 15 s blowdry

8. Measure offset between exposed squares and wanted position using optical microscope, then find exposed squared with SEM functionality

9. expose pattern (Fracture Resolution 25 nm)

10. Develop Samples
    (a) 70 s in MIBK:IPA, 1:3
    (b) 30 s IPA
    (c) 15 s blowdry

11. Deposit tungsten in sputterer

12. Lift-off in Acetone, 5 mins soaking, 10 s ultrasonic bath

13. Rinse with IPA
Appendix B

2D Grating Coupler

B.1 Introduction

For the design of an active polarization stabilization system an important component is a 2D grating coupler. Here, some experimental measurements for a number of fabricated 2D grating couplers are reported. I will begin with shortly summarizing the design process of the 2D grating couplers, introducing key variables. Then the measurement setup and the data analysis procedure is described. The key experimental results are given in the last section.

B.2 Design of 2D Focused Grating Coupler

The design of the used 2D focusing grating coupler is based on a previously published version by another group \[88\]. The idea of a 2D grating coupler is to couple the orthogonal polarizations of a fiber to two waveguides at an 90° angle. The interesting thing is that both polarizations are coupled to the TE mode of the waveguide due to geometrical considerations \[87\]. To reduce the long length required for tapering the wide grating mode into a nanowire for typical grating coupler one can use a focusing grating coupler where the grating ridges are bend to focus the light into the silicon waveguide \[100\].

The 2D focusing grating coupler is constructed by using the phase matching conditions of the 1D case shown in Eq. \[B.1\]. Then, the crossing points of this ellipse with a second one placed at a right angle are calculated. The principle is demonstrated in Fig. \[B.1\] where also some key dimensions are defined.

\[
r = \frac{NA}{n_e(1 - \epsilon \cos(\phi))}. \tag{B.1}
\]
Appendix B. 2D Grating Coupler

Figure B.1: A schematics of the 2D grating coupler. A few dimensions are defined. The green and blue lines are the two ellipses calculated using the phase-matching equation.

Here $N$ is an integer, $\lambda$ the vacuum wavelength, $\phi$ the angle within the silicon to the straight waveguide and $\epsilon$ the eccentricity of the ellipse. $n_e$ is the effective index in the grating region, and was calculated by a weighted average of the effective index of a 220 nm thick and 150 nm thick infinite silicon slab. The eccentricity $\epsilon$ is defined as follows:

$$
\epsilon = \frac{n_f \sin(\sqrt{2}\theta)}{\sqrt{2}n_e}.
$$

$\theta$ is the angle the incident fiber makes to the normal vector of the Si substrate and $n_f$ is the effective index of the fiber. One note here, the original equation in [88] does not have any $\sqrt{2}$ factor, because it is for a 1D coupler. Reference [88] does mention that a factor of $\sqrt{2}$ should be added for a 2D grating coupler. The way I added them the expected fiber angle it seemed to match FDTD simulations best. However, the experiment seems to suggest that only the factor in the denominator should be there. The $\sqrt{2}$ does not directly changes the performance, it only changes the optimal incident angle. It is known however, that grating couplers tend to work worse at larger incident angles, thus the changed angle has an indirect influence on the performance.

A schematic of the grating coupler and the construction method using the intersection of the ellipses can be seen in Fig. 5.4a. The different variations that were fabricated in this run are shown in Table B.1. Due to an outdated design rule document I had for the IMEC fabrication, the designs had a hole size with a minimum total area of 0.2 $\mu$m$^2$. This restricted the grating design to rather larger holes ($\text{SqLen} \geq 400$ nm, with an average distance between holes of only 600 nm), which I now believe to be not as efficient as smaller holes.
Appendix B. 2D Grating Coupler

Parameter | Size
---|---
$R_0$ | 20-30 µm
$R_1$ | $R_0 + 4$ µm
MFD | 12 µm
$\gamma$ | 45° (depends on MFD)
SqLen | 400-550 nm
Etch | Partial & Full
Shape | Square & Circle

Table B.1: Dimensions of the 2D Grating Coupler which were fabricated.

Figure B.2: The Gds layout of the two connected 2D-grating couplers.

B.3 Measurement Approach and Analyzing Technique

To test the performance two 2D grating couplers were connected using standard silicon waveguide as shown in Fig. B.2. The waveguide were purposefully offset in length, thus the output polarization will be different from the input polarization at most wavelengths. This was done to see an oscillation in the output spectrum, giving an easy way to characterize the polarization dependent loss of the grating coupler performance.

The coupling spectrum of the 2D-grating coupler around 1.55 µm was measured using a tunable laser system and an array of polarization maintaining fibers. The input polarization was chosen such that the light will be split 50:50 between the waveguides, i.e. the electric field is oscillating horizontally to the orientation of the grating couplers in Fig. B.2.

A typical output spectrum is shown in Fig. B.3. The blue curve is the experimental data and the predicted oscillations are visible. The peaks in the spectrum were identified using a script and a second order polynomial was fitted to the peaks and minima of the spectrum. A second order polynomial was used as a fit function and proved to be a very good approximation of the spectrum as visible in Fig. B.3. As visible in Fig. B.3 the two spectra cross at a wavelength of approximately 1.56 µm. By using the goodness of the fit as a parameter the crossing point of the spectrum are identified and the use of the maxima and minima between the two fits are switched for the two polarizations. One important note here, the insertion loss of a single coupler is approximately half the loss...
Appendix B. 2D Grating Coupler

Figure B.3: A typical output spectrum. This was for a partially etched circular shaped holes with 450 nm diameter and an R of 30 µm. The blue curve is the experimental data, the circles and crosses indicate the peaks identified by the algorithm and the red and purple curve is the fit, which correspond to two orthogonal polarizations.

in the plotted spectrum, as the spectrum shows loss for coupling into one coupler and coupling back out of a second coupler, which doubles the loss.

B.4 Results

Using the approach outlined the output spectrum for all fabricated couplers was analyzed. For all fully etched grating couplers I got very poor performance (>15 dB insertion loss per coupler) thus only the results for the partial etched couplers are plotted.

The results for a design angle of 15° are plotted in Fig. B.4 as function of the hole size (sqLen).

Different colored line correspond to different values for R as defined in Fig. 5.4a, as visible larger values slightly improve the performance, but not more then \( \approx 0.06 \text{ dB/µm} \) in the range of R values I scanned. Thus for compactness future 2D-grating couplers can be chosen to have a value of R=20 µm without loosing much performance.

As expected the center wavelength of the 2D-grating coupler gets smaller for larger hole sizes (compare Fig. B.4(a) and Fig. B.4(d)). A larger hole size reduces the effective index of the slab mode in the coupling region, which then reduces the center wavelengths. Due to the smaller area covered by a square with a given side length compared to circle with the same diameter, the center wavelength is smaller for the circles then for the square in the range of parameters considered here.

The Insertion loss reaches a minimum of 6.7 dB (Compare Fig. B.4(b)) for a partial etched circle with a diameter of 0.5 µm. This is comparable to previously published
Figure B.4: Performance of a 2D-grating coupler for a design angle of 15°. (a) and (d) show the center wavelength as a function of hole size, while (b) and (e) plot the minimum insertion loss, and (c) and (f) give the difference of the center wavelength for the two polarizations. (a), (b), and (c) are for circular shaped holes; (d), (e), and (f) for square holes. The legend shown in (a) and (b) holds true for all other plot as well, but was removed for clarity.
results ([101][87]). The insertion loss for the circular holes did not change significantly for different hole sizes (<1 dB), thus the design seems rather robust. The picture is different for the square holes (compare Fig. B.4(e)), this is likely due to fact that the couplers are not operating at the optimum, as discussed above due the change in area for a given side length versus diameter.

Looking at Fig. B.3 one can remember that the spectrum shifts for different polarizations. The difference in the center wavelength for the orthogonal polarizations for different grating couplers is shown in Fig. B.4(c) and Fig. B.4(f). It is fairly constant, but seems to be lower for the square coupler (≤2 nm vs. ≤5 nm). I am unsure about how this occurs, but [88] talks about getting better performance (smaller polarization independent loss) for non-circular scattering centers, which is the case here. However, looking at the results for the 20° coupler (B.5), both scattering center show the same shift of about 4 nm.

Otherwise the couplers with a design angle of 20° behaves very similar to the 15°, but the performance is worse. I also analyzed data for a grating coupler with an angle of 25°, but the performance there was so bad, that I decided not to include them here.

### B.5 Conclusion

Besides the mentioned needed correction for the design coupling angle as well as the smaller scattering centers for future optimization the following parameters should be of special interest. Due to time constrains I was not able to investigate them myself in this project.

- The hole shape: In this context I decided to limit myself to only a square and a circular hole shape, to not be overwhelmed with options. However, there is no obvious reason why these should be the best

- The difference between $R_0$ and $R_1$, or more specific the distance from the center at which scattering centers appear. For this design I used an educated guess of 4 μm (compared to 1D case), but a study on a few designs might yield some improvements.

- Additionally, the scattering strength *i.e.*, meaning the width/shape of the scattering center can be varied as a function of the center to form a more concentrated gaussian beam.
Figure B.5: Performance of a 2D-grating coupler for a design angle of 20°. (a) and (d) show the center wavelength as a function of hole size, while (b) and (e) plot the minimum insertion loss, and (c) and (f) give the difference of the center wavelength for the two polarizations. (a), (b), and (c) are for circular shaped holes; (d), (e), and (f) for square holes. The legend shown in (a) and (b) holds true for all other plot as well, but was removed for clarity.
• The known approaches such as chirping of the grating for bandwidth increase could be implemented.
Appendix C

3 dB Adiabatic Coupler

A schematics which gives the used dimensional parameters is given in Fig. C.1. The starting values used in the simulation are given in Table C.1. The starting values were suggested by Han Yun [67].

Table C.1: Original adiabatic coupler design parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{Input}</td>
<td>15</td>
<td>μm</td>
</tr>
<tr>
<td>L_{Taper}</td>
<td>50</td>
<td>μm</td>
</tr>
<tr>
<td>L_{Coupler}</td>
<td>175</td>
<td>μm</td>
</tr>
<tr>
<td>L_{Sbend}</td>
<td>10</td>
<td>μm</td>
</tr>
<tr>
<td>w_{Wg}</td>
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<td>nm</td>
</tr>
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<td>w_{1}</td>
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<td>nm</td>
</tr>
<tr>
<td>w_{2}</td>
<td>600</td>
<td>nm</td>
</tr>
</tbody>
</table>

The adiabatic coupler which was used in my layout is based on a previous design from Prof. Chrostowski Group [67] for a waveguide thickness of 220 nm with a partial etch in some areas of 90 nm down to 130 nm silicon thickness. However, their design was for a different slab thickness (130 nm) than the one which was available in my fabrication run (150 nm). After simulating the unchanged design in the Lumerical Mode Propagator tool, I noticed some ripples in the transmission spectrum, which would have cause the polarization adapter system to perform suboptimal.

The simulation results of the unchanged design are summarized in Fig. C.2. The transmission as a function of wavelength of the two outputs oscillates between 0.38 to 0.62 (Fig. C.2(a)) which is too large for my application. The source of this oscillation can be identified by looking at the in plane power profile in Fig. C.2(b) at a wavelength of 1.55 μm. A beating pattern can be observed which is indicative of a standard directional coupler design. As explained the directional coupler response should be suppressed by
having a large enough difference between the two input waveguide widths. In the original
design this was 400 nm and 600 nm respectively.

The performance could be large improved by changing the input waveguide width to
350 nm and 650 nm respectively. The results of this simulation are shown in Fig. C.3
The ripples in the transmission are completely removed (a) and there is no beating in
the in-plane power flow (b) visible.

To ensure optimal performance I also checked if other design parameters are optimally
chosen for the new slab thickness. To quantitatively compare different couplers the
average deviation across the wavelength range of interest is defined as follows,

\[
\text{DEV} = \frac{1}{N} \sum_{i=1}^{N} |T_i(\lambda) - \bar{T}|.
\] (C.1)

Here, \( \bar{T} \) is the average transmission across the wavelength range of interest, \( N \) is the
number of data points and \( T_i(\lambda) \) is the transmission at the wavelength \( \lambda_i \) as calculated
using the Lumerical MODE Propagator.

Figure C.4(a) gives \( \text{DEV} \) and the average coupler loss in dB as a function of the input
taper length (\( L_{\text{Taper}} \)). While the coupler loss is fairly constant over the range of scanned
lengths, the deviation from an even splitting changes a lot. The deviation does not drop
below 5% until the previous taper length of 50 \( \mu \text{m} \) and stays constant thereafter. Thus
the fabricated coupler will have a taper length of 50 \( \mu \text{m} \).

As the next parameter the s-bend length (\( L_{\text{S-Bend}} \)) was changed and the results are
plotted in Fig. C.4(b). The results show that an increase of the s-bend length at the
output to 15 \( \mu \text{m} \) helps reducing the coupler losses to \( \sim 0.1 \text{ dB} \). The deviation from
optimal splitting does not change significantly over the scanned lengths.

At the beginning of the coupler the top waveguide gets widened, while the bottom
one gets narrowed to allow for the adiabatic transition. The length of this section \( L_{\text{Input}} \)
was scanned next and is plotted in Fig. C.5(a). Varying the lengths slightly changes the
total loss of the coupler from 0.1 dB to 0.05 dB, but otherwise does not have a large
effect on the performance thus it will just be kept at 15 \( \mu \text{m} \), the original value.
Lastly the actual coupler length $L_{\text{Coupler}}$ was analyzed. Here the adiabatic transition occurs and a too short length will cause coupling between the odd and even supermode and create deviations from the flat broadband response wanted. The results are plotted in Fig. C.5(b). As expected the coupler length has a large impact on the average deviation, but only a small effect on the total loss. Slightly problematic here is that, there is no safe point, the deviation gets asymptotically better for longer length. Thus one can get very good performance for the price of a very long device. I choose to use a coupler length of 155 $\mu$m to get a very high performance device. One could likely reduce this by 20-50 $\mu$m, without comprising the performance too strongly, but I decided to be on the safe side, as my goal was a functioning polarization transparent device, not necessarily the smallest one.

The final device dimensions are summarized in Table C.2.
Appendix C. 3 dB Adiabatic Coupler

Figure C.3: (a) Transmission of the redesigned adiabatic coupler design as a function of wavelength with a slab thickness of 150 nm. (b) Powerflow in the plane of the coupler for the same simulation.

Table C.2: Final adiabatic coupler device dimensions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
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<td>µm</td>
</tr>
<tr>
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<tr>
<td>w&lt;sub&gt;2&lt;/sub&gt;</td>
<td>650</td>
<td>nm</td>
</tr>
</tbody>
</table>
Figure C.4: Deviations from an optimal coupling (blue curve) and coupler loss (red curve) as a function of input taper lengths (a) and output s-bend length (b). Symbols are simulation results, while the curve is a guide to the eye.

Figure C.5: Deviations from an optimal coupling (blue curve) and coupler loss (red curve) as a function of input mode converter length (a) and coupling region lengths (b). Symbols are simulation results, while the curve is a guide to the eye.
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