Efficient Light Coupling Techniques for Integrated Photonics

by

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

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Abstract

Given the fact that efficient and compact light emitters on a silicon (Si) platform yet do not exist, in most cases, light is still coupled to photonic chips from an external source (i.e. off-chip lasers) through single mode optical fibers (SMF). In this thesis, my investigations are focused on the problem of efficient light coupling to nano-photonic devices of different types. I propose and demonstrate a few compact on-chip solutions to efficiently couple light to specific modes of conventional photonic devices.

The size mismatch between an optical fiber mode and the on-chip nano-photonic/plasmonic mode of a photonic circuitry is the major contributing factor to an inefficient fiber-to-chip coupling. Additionally, due to the inherent birefringence of the on-chip waveguides (i.e. silicon-on-insulator waveguides) the coupling efficiencies are also polarization dependent. In this thesis, I propose and demonstrate a compact bilayer inverse taper edge-coupler with enhanced fiber-to-chip coupling efficiencies for both TE and TM polarizations of commercial Si photonic circuitry.

The current commercial practice of CMOS-photonics integration is limited to separate fabrication of the respective devices and connecting them by chip-to-chip interconnect systems. In this thesis, I propose and demonstrate a broadside beam routing mechanism in the telecom wavelength using a high index dielectric (i.e. Si) micro-prism structure. I extended the design to an elastic PDMS
(Polydimethylsiloxane) platform to achieve beam scanning capability in both telecom and visible wavelength ranges diversifying its applications.

I have further extended my work to the field of plasmonics and have designed a compact and highly efficient surface plasmon polariton (SPP) mode excitation scheme at the telecom wavelength regime using a gable shaped Si-tip with an optimized geometry. Fabrication of the Si-tip is compatible with standard Si processes. I have demonstrated the effectivity of the proposed scheme via a proof-of-principal experiment showing the high efficiency excitation of the SPP mode at an Au/SiO$_2$ interface. Furthermore, I present a detailed design of an SPP excitation device capable of efficiently exciting an SPP mode at an Au/air interface, facilitating an easy access to the excited SPP mode from the outside environment, making it more suitable for plasmonic sensing applications.
Acknowledgement

There are quite a few people who helped me walk through the course of my PhD years successfully. I will start with thanking my parents for always being there and encouraging me and giving me the confidence that I can overcome all the obstacles I faced in the past few years. Their upbringing taught me not to face life, but take it in stride and enjoy every moment of it. I am thankful to them for being who they are. I dedicate this thesis work to my parents Mrs. Radha Dewanjee and Mr. Mrinal Kanti Dewanjee.

In a PhD student’s graduate life, the first couple of years are vulnerable times since, in those years, they go through the learning curve that helps them figure out their own invention/innovation. I am thankful to two people for helping me out during those years of mine – Dr. Muhammad Zulfiker Alam and Dr. Jan Niklas Caspers – two alumni from our group. I can’t express enough gratitude to acknowledge their help in learning both optical simulation and fabrication processes for my PhD work. Special thanks to Niklas for teaching me to work with complicated multi-beam optical setups.

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At last, I want to convey my utmost gratitude to the two most important persons actively contributing towards the successful completion of my PhD – my two supervisors: Prof. Mo Mujahidin and Prof. J. Stewart Aitchison. They have guided me through all the ups and downs that I have faced in the last few years and didn’t lose confidence over my capability. Above everything, I want to mention that, besides being amazing supervisors to work with, they are two outstanding human beings who can connect with their students at a humane level. They have taught me how to be a good scientist, but more importantly, they actively took interest in teaching me how to be a better person. This is what made my PhD experience so smooth and outstanding and given another chance, I would want to have it the same. I couldn’t have reached this far without their supervision.
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<td>BI</td>
<td>Bilayer Inverse</td>
</tr>
<tr>
<td>CMP</td>
<td>Chemical mechanical polishing</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous wave</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defense Advanced Research Project Agency</td>
</tr>
<tr>
<td>DRC</td>
<td>Design rule check</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep reactive ion etching</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite difference time domain</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half max</td>
</tr>
<tr>
<td>IPA</td>
<td>Iso-Propyl Alcohol</td>
</tr>
<tr>
<td>IPE</td>
<td>Internal photo-emission</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-red</td>
</tr>
<tr>
<td>LSPR</td>
<td>Localized surface plasmon resonance</td>
</tr>
<tr>
<td>MFD</td>
<td>Mode field diameter</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>PML</td>
<td>Perfectly Matched Layer</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Micrograph</td>
</tr>
<tr>
<td>SMF</td>
<td>Single mode optical fibers</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon-on-insulator</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>---------</td>
<td>------------</td>
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<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>TNFC</td>
<td>Toronto Nano-Fabrication Center</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>VCSEL</td>
<td>Vertical cavity surface emitting lasers</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiplexing</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>SPP</td>
<td>Surface plasmon polariton</td>
</tr>
<tr>
<td>PDL</td>
<td>Polarization Dependent Loss</td>
</tr>
</tbody>
</table>
Chapter 1. Introduction

The journey of integrated optical circuitry started dating back in the 1970’s with the vision of an optical super-chip that contains a variety of integrated optical components i.e. light sources, modulators, passive optical components and detectors (Miller, 1969). Since then, the research community has experimented with different materials as a basis for the development of optical circuitry. However, the dominance of silicon (Si) as the semiconductor platform for the electronics industry has led to the investigation of Si as the material platform for integrated photonic circuitry with the hope of a seamless integration of electronics and photonics on the same chip (Reed, Headley, & Png, 2005). The development of the Si photonic industry has picked up pace since the early 2000’s due to the increased investment by the industries and governments all over the world (Soref, 2006). In 2004, the Defense Advanced Research Project Agency (DARPA) in the USA largely invested in 1.55 \( \mu \text{m} \) (wavelength) Si-phononics (Soref, 2006). In subsequent years, further investments and successes have been reported in the development of 1.55 \( \mu \text{m} \) Si photonic circuitry (Soref, 2006). However, the photonics industry also makes use of different other material systems including compound semiconductors (InP – Indium Phosphide, GaAs – Gallium Arsenide), elementary semiconductors (Si, Ge – Germanium), Silica (SiO\(_2\)), rare earth doped glasses and polymers (Liang & Bowers, 2010). The use of such diverse material systems is mostly due to the difficulties associated to developing an efficient light emitting device on a Si platform (Liang & Bowers, 2010). The major challenge in developing an on-chip Si light emitter is the indirect bandgap of Si. Thus, the focus of the semiconductor laser research has been directed towards compound semiconductor systems rather than Si (Liang & Bowers, 2010).

Nevertheless, there have been parallel interests in the Si-phononics community to overcome the challenge of non-radiative recombination due to the indirect bandgap of Si in order to build a seamless photonics system, with an on-chip light emitting device. In 2004, Boyraz et al. have demonstrated a pulsed Si Raman laser (Boyraz & Jalali, 2004) followed by continuous wave (CW) Raman gain in a silicon-on-insulator (SOI) waveguide (Jones, et al., 2005) and a low threshold CW Si Raman laser (Rong, et al., 2005). There have been demonstrations of epitaxial lasers on Si such as the report of Ge-on-Si laser by Liu et al. (Liu, Sun, Camacho-Aguilera, Kimerling, & Michel, 2010) and hybrid Si lasers such as the distributed feedback Si evanescent laser by (Fang,
Lively, Kuo, Liang, & Bowers, 2008). More recently, there are reports of further research on III-V band-edge laser cavities on SOI (Lee, Kim, Farrel, & Senanayeke, 2016) and direct bandgap light emission from strained Germanium nano-wires on silicon substrates (Petykiewicz, et al., 2016). Despite these brilliant efforts, on-chip sources are still not commercially available for Si photonic chips due to some specific short-comings such as low power-efficiency and high-temperature operation. The use of a thick oxide layer in photonics SOI wafers limits the heat conduction making the thermal management difficult (Thomson, et al., 2016). Therefore, the Si-photonics industry is still dependent on off-chip sources of light in the telecom spectrum.

1.1 Fiber to Si Waveguide Light Coupling Techniques

Typically, in optical datacom circuitry, light is collected and carried to the Si photonic chips from off-chip sources through single mode optical fibers (SMFs). This flow of optical power can be from an off-chip light emitter delivering the career wavelength to the Si circuit through a fiber on the transmission side, or, this can also be an incoming optical data traffic from a fiber to a receiver circuit feeding to a detector. The major challenge in achieving an efficient fiber-to-chip coupling is the mismatch between the fiber mode-size and mode-index to those of the Si-waveguide modes on a photonic chip (Thomson, et al., 2016). Thus, improving the fiber-to-chip coupling efficiency is a difficult task in Si-photronics (Chen, Li, & Tsang, 2011).

In a laboratory setup, light can be coupled from an external source to an on-chip SOI waveguide by simply aligning and focusing a free space beam on-to the cleaved facet of the chip (where the waveguide edge lies). This scheme is also known as end-fire coupling. Figure 1.1-a shows a typical setup of end-fire coupling (Hunsperger, 2009). Free-space to waveguide coupling can also be achieved by total internal reflection of the beam from a facet of a high refractive index prism which lies near the top surface of a waveguide. This scheme is also known as evanescent coupling because it makes use of the evanescent wave penetrating through the small gap ($s$ in Figure 1.1-b) between the prism and the waveguide. Since, for certain $\theta$ (Figure 1.1-b), the component of the totally internally reflected beam inside the high index prism, in the direction of the waveguide propagation (‘z’ axis as shown in Figure 1.1-b) has sufficient momentum to match the waveguide mode index, coupling to the corresponding propagating mode inside the waveguide can be achieved as shown in Figure 1.1-b.
However, in commercial integrated photonics, coupling from an SMF to an SOI chip is a more common scenario. There are two popular approaches to efficiently couple light from the fiber to the photonic chips, namely: – edge/butt coupling and diffractive grating coupling (Thomson, et al., 2016). Typically, in an edge/butt coupling scheme the fiber facet is held against the cleaved facet of the SOI chip aligned to the waveguide (that ends at the cleaved facet). Edge coupling is an existing standard technique for III-V device industry (Song, Fernando, Roycroft, Corbett, & Peter). Conforming to the III-V standards, edge couplers (tapered waveguide couplers) are widely investigated for fiber to waveguide coupling in Si photonic platform as well. Figure 1.2-a shows a typical setup for edge coupling to an SOI waveguide. However, Si waveguides have higher index-contrast than III-V waveguides. Therefore, the mode-size in a single mode Si waveguide is much smaller than the III-V counterpart resulting in a bigger mismatch with the fiber mode size. Thus, an efficient fiber-to-waveguide edge coupling is a bigger challenge in Si photonics as compared to III-V photonics. Due to the significant mismatch of the size and effective index of the modes between the fiber and SOI waveguides, this scheme results in an inefficient coupling. To overcome this challenge, a tapered mode converter is attached to the end of the SOI waveguide which helps the waveguide mode to evolve such that mismatch of shape and effective index between the fiber mode and the converted waveguide mode is minimized. Several techniques have been proposed in the literature for designing such mode converters (Hunsperger, 2009). Inverse taper coupler (Almeida, Panepucci, & Lipson, 2003) is the most popular scheme for such mode converting in Si
photonics to achieve enhanced fiber-to-chip coupling due to their compactness and broadband properties. In the inverse taper scheme, waveguides are narrowed down towards cutoff to increase the mode size which results in a better overlap with the incoming fiber mode. A more detailed literature review and description of the inverse taper edge coupling technique can be found in the next section (1.2) and in Chapter 2 (section 2.1).

![Image](image_url)

**Figure 1.2:** a) A setup for an edge coupling to a Si waveguide on an SOI platform. Image is obtained from (Kopp, et al., 2011) b) Schematic of a light coupling to an SOI waveguide using grating couplers. Image is obtained from (Xu, et al., 2011).

Coupling through diffraction grating couplers is the other popular technique used to achieve efficient fiber to waveguide coupling in Si photonics. In such couplers, the diffraction gratings are designed to provide additional momentum to the incoming beam of light (released from fiber) to match to the momentum of the waveguide mode. Often, to ensure unidirectional coupling, the grating teeth are designed to achieve maximum coupling for an angled incidence using the phase match condition. Figure 1.2-b shows a typical setup for fiber-to-waveguide coupling through diffraction grating couplers. A more detailed discussion on the design of a grating coupler using the phase match equation can be found in section 4.6 in Chapter 4. Grating couplers have been widely investigated as an efficient fiber-to-chip coupling tool in Si photonics and significant improvements have been made on coupling efficiencies by engineering the grating properties (Mekis, et al., 2011). Baets *et al.* have proposed apodized grating couplers for efficient and compact fiber-to-waveguide coupling in Si photonics (Taillert, Bienstman, & Baets, 2004). Arched grating teeth couplers have also been proposed in conjunction with an adiabatic tapered waveguide to allow the coupled light to focus into the waveguide (Mekis, et al., 2011). Since typical grating couplers are polarization sensitive, there is a characteristic polarization dependent loss during
fiber-to-chip coupling (or vice versa) since the fiber mode contains both the \( s \) and \( p \) polarizations. To overcome this problem, polarization-splitting grating couplers have been proposed (Mekis, et al., 2011). Such couplers comprise of a grating structure that is periodic in two dimensions. It couples the two \( (s \) and \( p \)) polarizations to two different waveguides oriented at 90° to each other. Grating couplers with subwavelength features have also been investigated for achieving broadband operation [ (Zhong, et al., 2014), (Halir, et al., 2014)]. Multi-layered gratings have also been proposed and demonstrated for efficient fiber-to-chip light coupling in nitride-on-silicon platform (Sacher, Huang, Lo, & Poon, 2015).

![Figure 1.3](image)

*Figure 1.3: Classification of source-to-chip light couplers in Si photonics.*

Figure 1.3 above summarizes the classification of fiber-to-chip light coupling techniques in Si photonic circuitry. As mentioned earlier, edge-coupling and grating coupling are the most widely adopted coupling techniques in commercial Si photonics. However, the choice of an edge-coupler or a grating coupler for fiber-to-chip coupling is application specific and cost dependent. For example, edge-couplers can have a high coupling efficiency and large bandwidth of operation, but they have to be placed at one edge of the chip and lacks the provision of testing components on the chip. Grating couplers can be placed anywhere on the chip, typically they occupy smaller real estate on the chip, but have narrow bandwidth of operation and the incoming fiber has to be held at a certain angle of incidence (Chen, Li, & Tsang, 2011). Besides such technology specific problems there exists another problem of handling the polarization of the incoming light from the coupling fiber for both techniques. Unless a polarization maintaining fiber is being used (which is rarely the case for commercial coupling), the mode inside the SMF used to couple light from external source to the chip is un-polarized – meaning it contains both \( s \) and \( p \) polarizations. In
terms of a rectangular cross-sectioned Si-waveguide, these polarizations are popularly named as the TE (Transverse Electric) and TM (Transverse Magnetic) polarizations. In a perfect world, the fiber-to-chip coupling should be insensitive to the incoming polarizations (TE or TM) contained in the fiber mode. But that is not the case since a single mode Si-waveguide is inherently birefringent. Therefore, fiber-to-chip coupling is always sensitive to the incoming polarization. In the commercially available SOI wafers the height of the Si guiding layer is limited to 220 nm (Lim, et al., 2014). Hence, it is fundamentally impossible to reduce the birefringence in the SOI-based Si-waveguides since there exists no well-confined mode in a Si-waveguide with a cross section of 220 nm X 220 nm (the typical single mode SOI waveguide is 450 nm – 500 nm width by 220 nm height). As a consequent, the fiber-to-chip coupling mechanism should be polarization insensitive so that maximum amount of power, in both the polarizations gets coupled to the corresponding modes of the Si-waveguide. Since grating couplers are comparatively narrowband devices and require an out-of-plane setup to couple light they are difficult to align and sensitive to misalignment in a practical packaged device. In my work, I chose to work on the development of an efficient edge-coupler for Si-photonics with enhanced coupling efficiencies for both TE and TM polarizations.

1.2 A Bilayer Inverse taper edge-coupler for Si-photonics

For the first project in this thesis, I have successfully proposed and demonstrated a bilayer inverse taper edge-coupler with enhanced coupling efficiencies for both TE and TM polarizations on an SOI platform. A detailed discussion on the design, fabrication and characterization of the proposed edge-coupler is presented in Chapter 2 of the thesis. Here, I start with a brief introduction of inverse taper edge-couplers.

Figure 1.4: a) Schematic of a fiber to Si-waveguide coupling (geometry drawn not to scale. b) Mode at the tip of a focused fiber. c) TE mode of a single mode SOI waveguide. The modes in part-b and part-c are drawn to the same scale.
Typically, single mode SOI waveguides have a cross-sectional dimension of 220 nm height by 450-500 nm width. For such dimensions, both the TE and TM modes are well-confined to the Si-waveguide at a wavelength of 1550 nm. In other words, such single mode waveguides have submicron mode sizes while the input mode field diameter (MFD) of a commercially available fiber is \( \sim 10 \mu m \). The MFD of a focused fiber (typically used for edge coupling) is \( \sim 5 \mu m \). Figure 1.4 shows the geometrical comparison (not drawn to scale) and the mode size comparison of the fiber and Si-waveguide mode underlining the size mismatch. Towards the end of 2002, T. Shoji et al. (Shoji, Tsuchizawa, Watanabe, Yamada, & Morita, 2002) and in 2003, Almeida et al. (Almeida, Panepucci, & Lipson, 2003) proposed an inverse taper edge-coupler with considerably high coupling efficiency for Si-photonics to deal with the problem of mode-size mismatch.

In an inverse taper coupler, the width of the SOI waveguide is narrowed down to push the waveguide mode towards cut-off. Therefore, the mode becomes loosely bound to the waveguide and spreads out to the cladding of the waveguide. This results in an improved match between the mode sizes of the incoming fiber and that at the tip of the inverse taper coupler, leading to a better coupling. Figure 1.5 shows the schematic diagram of a typical inverse taper coupler. Since the first demonstration of the inverse taper coupler, there have been several reports aimed at improving the performance of such edge-couplers by engineering the geometry of the narrowed down waveguides and the cladding layer around it. A more detailed review of the literature on inverse taper couplers is presented at the beginning of Chapter 2.

![Figure 1.5: Schematic diagram of a conventional inverse taper edge-coupler in Si-photonics. Typically, on an SOI platform this inverse taper structure sits on a 2 \( \mu m \) bottom oxide layer of SiO\(_2\) and, also covered by a cladding layer of SiO\(_2\).](image)

While engineering the geometry of the inverse taper for a better performance, one does not have unlimited freedom to work with the height of the waveguides, due to the commercial fabrication foundry rules for Si-photonics. The reason behind this limitation is – firstly, the optimized SOI
wafer geometry only allows a waveguide height of 220 nm and secondly, there are only 2 options for partially etched waveguide heights. The design rule check (DRC) protocol of commercial SOI photonics foundries offers two standards – a 70 nm partial etch and a 150-nm partial etch (Europractice, n.d.). Hence, the leeway to optimize the geometry of the Si layer of the taper is somewhat limited to the width of the inverse taper waveguide at three fixed heights (70 nm, 150 nm and 220 nm). The proposed bilayer inverse taper edge-coupler in Chapter 2 has a tip dimension of 150 nm height (using the 70 nm etch depth DRC rule) and 150 nm width. The symmetry of the tip dimension facilitates improved coupling for both polarizations from the incoming fiber.

Figure 1.6: Schematic Diagram of the bilayer inverse taper coupler proposed in Chapter 2

Figure 1.6 shows the schematic diagram of the proposed bilayer inverse taper coupler in Chapter 2, where I discuss the design, fabrication, and experimental demonstration of the compact (30 µm long) bilayer, inverse taper, edge-coupler with a coupling loss of 1.7 dB. To comply with the commercially available focused fiber geometry, the input fiber in my measurement setup had an MFD of 5 µm, from which light was coupled to a single mode Si-waveguide of 500 nm width and 220 nm height. To compare the performance of our bilayer inverse taper with an existing comparable design in literature, I also fabricated (using the same fabrication facilities) a conventional inverse taper as it was presented in Ref. [ (Almeida, Panepucci, & Lipson, 2003)].

1.3 A Compact and Efficient SPP Excitation Scheme

As discussed in the previous section, all-dielectric SOI based Si photonic circuitry have been widely investigated and currently are being commercially fabricated for applications in data
communication links and devices. However, due to the diffraction limit, there is a limit of the allowable minimum dimension of such circuitry. Silicon based plasmonic components have been widely investigated for the miniaturization of integrated photonic devices since they offer a high degree of confinement of light (Soref, 2006). Alam et al. thoroughly investigated the metal-dielectric hybrid plasmonic platform for designing on-chip optical components like on-chip polarizers and directional couplers (Alam, Aitchison, & Mojahedi, 2014). Furthermore, the field of plasmonics has been investigated for its potential application to the miniaturization of active components of integrated circuitry such as plasmonic modulators (Schuller, et al., 2010), (Lin & Helmy, 2015) and plasmonic detectors (Berini, 2014), (Casalino, Cappola, De La Rue, & Logan, 2016).

In addition to finding applications in integrated photonics for data communication, the field of plasmonics has been widely investigated for optical sensing. Plasmonic sensors typically utilize the propagating SPP mode or the localized surface plasmon resonance (LSPR) to sense the change in refractive index of a medium. Depending on the excitation setup of the surface plasmon in the sensor, one may deploy an angle resolved measurement, or a wavelength resolved measurement of the change in the refractive index.

1.3.1 Common SPP excitation techniques

In a typical chip-based SPP sensor setup, as well as SPP based circuitry, the main drawback is the need of an efficient and compact SPP excitation setup. The major challenge in exciting an SPP mode is to provide additional momentum to a freely propagating light-wave in a dielectric medium to match to the effective momentum of an SPP mode at a metal/dielectric interface. Typically, prism-coupling in the Otto or Kretschmann configurations (Figure 1.7) are used to couple SPP mode at a metal/dielectric interface. However, the Kretschmann configuration is a more popular choice among the two, to excite the propagating surface plasmon polariton mode in the SPP based sensors (Li, Cushing, & Wu, 2015). The major disadvantage of SPP excitation using the Kretschmann configuration is the required bulky setup which makes it incompatible to compact SPP based devices.
On the other hand, grating couplers provide a more compact solution of the SPP excitation problem. Typically, in such setups, the grating periods are designed to provide sufficient momentum to the incoming beam to be coupled to the SPP mode utilizing phase matching. Various further modifications of the simplistic grating structures have also been investigated to improve the coupling efficiency. Figure 1.8 shows the schematic diagram of a grating structure, investigated by T. Lu et al. (Tianran Liu, 2014), with a high free space to SPP coupling efficiency.

Grating couplers are compact devices, but they require a specific angle of incidence for efficient coupling. Moreover, grating couplers provide a narrow-band coupling since they are diffraction based devices. Different metallic nano-structures like nano-apertures in metals (Jing Yang, 2014) and metallic nanotips (Bayarjargal N. Tugchin, 2015) have also been investigated as means of compact excitation of surface plasmon polaritons. However, they are generally inefficient processes, hence, are not suitable for commercial applications. For on-chip integrated photonic circuitry, mode conversion in an adiabatic fashion has also been used to excite an SPP mode from
propagating dielectric waveguide modes [ (Guo, et al., 2009), (Charbonneau, Lahoud, Mattiussi, & Berini, 2005)].

Besides propagating SPP modes, one can excite localized surface plasmon resonance (LSPR) in metallic nanoparticle clusters by simply shining collimated light on it. Due to the challenges of the various SPP coupling techniques discussed above, researchers have investigated such LSPR based sensors for the simplicity of the SPR excitation (Li, Cushing, & Wu, 2015). But SPP’s, as the means of sensing, provide versatility such as self-referencing capability and ability of differentiating between bulk and surface sensing (Bahrami, Maisonneuve, Meunier, Aitchison, & Mojahedi, 2013). Therefore, further investigation for the development of a highly efficient and compact SPP excitation technique is of high importance for various applications including sensing and miniaturized integrated optical circuitry. Figure 1.9 below summarizes the different techniques of coupling of surface plasmons.

**Figure 1.9: Classification of Surface Plasmon coupling.**

### 1.3.2 Proposed SPP Excitation Scheme

In Chapter 4, I propose and demonstrate a compact and highly efficient SPP excitation mechanism which can convert as high as 52% of the input power (at 1550 nm wavelength) to the characteristic single interface SPP mode of an Au/SiO$_2$ interface. A proof-of-principal experiment is also presented in Chapter 4 that demonstrates the effectiveness of the proposed scheme. Figure 1.10 shows the schematic diagram of the proposed SPP excitation scheme.
Figure 1.10: Schematic of the proposed SPP excitation scheme in Chapter 4

The presented SPP excitation scheme offers substantial improvement of SPP excitation efficiency over the other proposed techniques in the literature regarding two factors – a) compactness and on-chip integration compatibility and, b) the efficiency numbers are measured with respect to the total amount of power in the input beam as opposed to considering a portion of the input power incident on a sub-wavelength geometry of the SPP excitation scheme such as a nano-slot (Jing Yang, 2014). Additionally, this scheme offers a compact but highly efficient SPP excitation at the telecom wavelength which makes it suitable for application in photonic circuit components such as plasmonic detectors.

As evident from Figure 1.10, the technique presented in Chapter 4 excites the SPP mode at the bottom interface between the Au and the SiO$_2$ layer which, although can be useful for integration with CMOS-Si photonics circuitry, makes the excited SPP mode less accessible to external environment for applications like optical sensing. Furthermore, the excited SPP could be contaminated by scattered light from the Si-tip which eventually did not get coupled to the SPP mode. To overcome the challenges, in Chapter 5, I present the design of a reduced noise SPP excitation scheme with more accessibility to the excited SPP mode. This design is a modification of the proposed scheme presented in Chapter 4.
1.4 CMOS–Si-photonics Integration

Besides efficient coupling of light to certain modes of a photonic circuitry from an external source, integrating Si-photonics with complementary metal oxide semiconductor (CMOS) circuitry on the same chip can be advantageous for many applications. However, such integration is still not ubiquitous in the semiconductor industry. This could majorly be attributed to the fact that a high yield process flow involving the simultaneous fabrication of both the electronic and optical components on the chip is yet to be established. Although both photonic and electronic processes can be carried out in the same environment, the interaction of such processes with one another might result in performance degradation of the on-chip devices (Izhaky, et al., 2006). Furthermore, the SOI substrate used for photonics has a thicker bottom oxide (BOX) layer as compare to CMOS SOI to reduce waveguide loss. In addition, there exists a significant mismatch of sizes between the electronic (sub 100 nm) and photonic devices (0.1–1 µm) on the chip, thereby resulting in a mismatch of integration density (Lim, et al., 2014). One possible solution of such integration incompatibility is to separately fabricate the photonic and electronic components on different chips and establish inter-chip communication by making use of chip-to-chip interconnect technologies such as wire bonding, flip-chip bonding or even 3D stack technologies (Lim, et al., 2014). Therefore, in addition to efficient coupling, on-chip/chip-to-chip beam routing is also a highly important field of research for integrated photonics. Besides the two coupling techniques demonstrated in this thesis, the results of an investigation are also presented on designing an on-chip beam routing technique to route a vertical beam towards the broadside direction. However, to present the research in a chronological order, in Chapter 3 (before discussing the SPP excitation technique in Chapter 4), I discuss the design, fabrication and characterization process of the above-mentioned beam routing scheme. Then, using a pattern transfer method, the replication of the same geometry on a flexible PDMS film surface is presented which provides the feature of a beam scanning capability in the broadside upon application of lateral stress on the PDMS film. This technique of beam direction control can be very useful in different applications such as free space interconnects, for 3D integration of hybrid photonic circuits. The stretchable PDMS structures can be used to efficiently excite SPP modes in the visible wavelengths.
1.5 Contributions

In a summary, I have made the following contributions during my PhD work which I present in this thesis:

- Demonstration of a bilayer inverse taper edge-coupler with high fiber-to-chip coupling efficiency for Si-photonics.
- Design, development of the fabrication process and characterization of a compact, high efficiency surface plasmon polariton (SPP) excitation mechanism enabling efficient miniaturization of SPP excitation scheme.
- Design, analysis and development of a fabrication process of a very compact and highly efficient surface plasmon polariton (SPP) excitation mechanism with direct access to the excited SPP mode.
- Demonstration of an on-chip beam routing and a PDMS beam scanning mechanism using micro-prism structure.

1.6 Thesis organization

In the big picture, this thesis presents my original work on the development of efficient coupling techniques for integrated photonics. The original contributions made in this thesis are summarized in section 1.5. The different coupling techniques/devices presented are connected to each other through the thread of the common goal of efficiently delivering light to specific mode of a photonic device (both dielectric and surface plasmon polariton waveguides have been considered) from an off-chip input such as a free space Gaussian beam or a fiber mode of large cross section. Here, in this thesis, I present my work on the design, fabrication and characterization of the three different devices while I introduce the design and fabrication outline of a fourth device. For a quick overview and an easy accessibility for the readers, I present the organization of the thesis below:

**Chapter 2** – presents the detail discussion on the design, fabrication and characterization of a bilayer inverse taper edge-coupler for enhanced fiber-to-chip coupling in Si-photonics.

**Chapter 3** – presents the detail discussion on the design, fabrication and characterization of a broadside beam routing technique which is extended to an elastic PDMS platform to achieve beam scanning.
Chapter 4 – presents the design, fabrication and characterization of a compact and highly efficient SPP mode excitation technique using a gable shaped Si-tip.

Chapter 5 – presents the design and a fabrication outline of an extension of the SPP excitation technique presented in Chapter 4 enabling the excitation of a more accessible and less noisy SPP mode at an Au/air interface.

Chapter 6 – presents my concluding remarks and some guidelines for extending the works presented in this thesis to future applications.
Chapter 2. A Bi-layered Inverse Taper Coupler for Si-photonics

Silicon (Si) Photonic circuitry are gradually stepping into the era of commercialization in parallel to electronics circuitry (although on a separate chip platform) and becoming an integral part of long and short haul communication. There have been numerous research efforts dedicated in developing optical counterparts of the electronic components of a communication link. Due to the low absorption loss in silicon (Si), 1550 nm is the ubiquitous choice of wavelength for optical communication. But unfortunately, because of the indirect bandgap properties of Si, there are no good sources of 1550 nm wavelength light on a Si-platform. Hence, light is delivered to the Si-photonics circuitry through a fiber. There are several factors impeding an efficient coupling of light from a fiber to a Si-waveguide which is an integral part of the Si photonic circuitry. In this chapter, I will introduce the design of a bi-layered inverse taper coupler which efficiently serves the purpose of coupling light from a single mode fiber to a single mode Si-waveguide. Then the fabrication and the characterization of the designed coupler will be explained in the latter part of this chapter.

2.1 Introduction

Efficient coupling of light from optical fibers to silicon (Si) photonic circuits is an important consideration when designing such circuits. The absence of a good source on Si platform requires light to be delivered to the Si-waveguides through single mode optical fibers (SMFs) from an external source (Kopp, et al., 2011). However, a substantial mismatch exists between the mode-sizes and mode-indices of a typical SMF and a single mode Si-waveguide. Such mismatches lead to inefficient coupling of light to the Si optical circuits.

Several techniques have been proposed for efficient coupling of light to Si-waveguides in a silicon–on-insulator (SOI) platform. Diffraction gratings [ (Ang, et al., 1999), (Régis Orobtchouk, 2000), (Chen & Tsang, 2009), (Mekis, et al., 2011), (Halir R. B.-M.-R.-X.-P.-F., 2014), (Wang, et al., 2014), (Sacher, Huang, Lo, & Poon, 2015)] and edge-couplers [ (Cheben, Xu, & Janz, 2006), (Chen, Doerr, Chen, & Tsung-Yang Liow, 2010), (Shoji, Tsuchizawa, Watanabe, Yamada, & Morita, 2002), (Almeida, Panepucci, & Lipson, 2003), (Cardenas, et al.)] are the more popular
techniques widely used for fiber to Si chip coupling. Diffraction gratings are generally narrow band and require an out-of-plane mechanism to hold the fiber at a specific angle to efficiently couple light into the Si-waveguides. On the other hand, edge coupling, through a taper, can produce a high coupling efficiency over a broad band of source wavelengths, in addition this method does not require an out of plane coupling mechanism. An adiabatically tapered waveguide in which both the width and height change, improves the mode matching between the fiber and the Si-waveguide, hence improving the coupling of the input light to the Si-waveguides [ (Doylend & Knights, 2012), (Dai & He, 2006), (Barkai, et al., 2008)]. This method, however, suffers from some drawbacks such as complex fabrication steps and large real estate on the chip.

A somewhat different approach from the above is the inverse taper coupler. In an inverse taper coupler, the input Si-waveguide cross-section is narrowed toward the edge of the chip so that the mode is pushed to cut-off. Thus, the mode size increases and becomes more loosely guided. Through careful design it is possible to better match the mode size of the Si-waveguide with the SMF mode, resulting in better coupling efficiency. In the literature, there are several reports on inverse tapers of various designs aimed at increasing the coupling efficiency between the SMF and Si-waveguide. First Shoji et al. [ (Shoji, Tsuchizawa, Watanabe, Yamada, & Morita, 2002)] and then Lipson et al. [ (Almeida, Panepucci, & Lipson, 2003)] proposed and demonstrated the idea of inverse taper edge-coupler with coupling efficiencies between 3 dB to 6 dB for a taper length of ~ 40 μm. Mcnab et al. used the same inverse taper coupler, optimized to couple light to the fundamental TE mode of a photonic crystal waveguide, with a coupling efficiency of ~ 2 dB [ (McNab, Moll, & Vlasov, 2003)]. Several groups have proposed and demonstrated efficient edge-couplers with additional modification of the cladding geometry of the inverse taper [ (Chen, Doerr, Chen, & Tsung-Yang Liow, 2010), (Galán, Sanchis, Sánchez, & J. Martí, 2007), (Khilo, Popović, Araghchini, & Franz X. Kärtner, 2010), (Pu, Liu, Ou, Yvind, & Jørn, 2010), (Fang, et al., Suspended optical fiber-to-waveguide mode size converter for Silicon photonics, 2010)]. Bakir et al. demonstrated less than 1 dB coupling loss from a fiber with a 3 μm MFD for their 200 μm long inverse taper arrangement which also shows a polarization insensitivity [ (Bakir, et al., 2010)]. In their work, Wood et al. presented a 7.5 μm long taper with cantilever beam and undercut structure on SOI with coupling efficiencies of less than 1 dB from a specialized 1.5 μm MFD fiber [ (Wood, Sun, & Reano, 2010)]. Lipson et al. also reported a 100 μm long simple inverse taper coupler with
a coupling loss of 0.7 dB per facet [ (Cardenas, et al.)], where they used a standard 5 μm MFD fiber for coupling. For the reader’s convenient, these results are tabulated in section 2.7 of this thesis in Table 2.2. I should also add that there are other reports of efficient edge-couplers with more complicated structures, using smaller MFD fiber [ (Fang, et al., 2010)].

Aside from the coupling efficiency there are two other important criteria determining the performance of an edge-coupler inverse taper – the length of the taper and the MFD of the coupling fiber. For an integrated optical circuit, the size of an optical component, i.e. the space occupied by a component on the chip, is an important consideration. In other words, it is always desirable to fabricate a device that is more compact; ideally, without scarifying performance. The other parameter affecting the coupling is the MFD of the coupling fiber which essentially causes the mode-size mismatch between the fiber and Si-waveguide. Commercially available SMFs, such as those used in optical communication systems have a MFD of ~10.4 μm while the lensed-facet SMFs, commonly used for fiber-to-chip coupling, have a MFD of ~5 μm. Finally, the simplicity of fabrication and compatibility with the commercial foundry fabrication rules are other considerations which should be kept in mind when designing a Si photonic device.

In this chapter I discuss the design, fabrication, and experimental demonstration of a compact (30 μm long) bilayer, inverse taper, edge-coupler with a coupling loss of 1.7 dB. The input fiber had a MFD of 5 μm, from which light is coupled to a single mode Si-waveguide of 500 nm width and 220 nm height. To compare the performance of our bilayer inverse taper with an existing comparable design in literature, I have also fabricated (using the same facilities) a conventional inverse taper as it was presented in Ref. [ (Almeida, Panepucci, & Lipson, 2003)].

### 2.2 Design of the Bilayer Inverse Taper

The basic idea behind an inverse taper, used to couple light to a waveguide on a chip, is to gradually reduce the waveguide cross-section to a certain point such that the guided mode is pushed toward cutoff. Under this condition two things happen: (1) the mode size gradually increases and (2) the mode effective index \( n_{eff} \) approaches that of the cladding. As the result of the increase in mode size, there is a better spatial overlap between the modes of the input fiber and the narrow waveguide. Because of the change in effective mode index there is a better match between the
mode indices of the input fiber and the waveguide. Both phenomena help the light to better couple from the input fiber to the waveguide.

![Figure 2.1: a) Simulated effective mode index as a function of Si-waveguide width for a waveguide height of 220 nm (dashed line) and 150 nm (solid line) with an oxide over-layer on the SOI wafer. b) Cross section of the tip dimension of Si-waveguide buried in SiO$_2$.](image)

To illustrate the operation of the bilayer taper I start by considering the change in effective indices, for the TE and TM modes of a Si-waveguide on SOI wafer. The variation of the effective indices for two different waveguide heights (150 nm and 220 nm) are plotted in Figure 2.1. There are two important observations to be made in Fig. 1. First, as the width of the Si-waveguide decrease, all the effective mode index curves approach the SiO$_2$ index of 1.44. At the same time, the effective index of a typical fiber mode is also close to the SiO$_2$ index; hence, the mismatch between the effective indices of the fiber and Si-waveguide can be dramatically reduced. Second, as evident in Fig. 1, for the 220-nm tall Si-waveguides, the two dotted curves (for TE and TM modes) do not have any overlap; therefore, there is a fair amount of birefringence (difference in $n_{\text{eff}}$ for TE and TM modes) for all widths. The birefringence is reduced when the waveguide width is reduced to 100 nm. The significant birefringence results in a significant difference between the coupling efficiencies for the TE and TM modes of the inverse taper. On the other hand, for a Si-waveguide with the height of 150 nm, the birefringence is substantially reduced for widths less than 180 nm. This is manifested by the overlapping portions of the green and orange solid curves in Figure 2.1-at regions where the waveguide width (horizontal axis) is less than 180 nm. This means that for waveguides with a transverse cross section of 150 nm by 150 nm, the birefringence is small while at the same time the effective mode index of the Si-waveguide matches closely that of the input fiber. Moreover, the choice of 150 nm by 150 nm is convenient, since it is compatible with the commercial fabrication rules.
Figure 2.2: Schematics of the proposed bilayer taper. (a) A 3D artistic impression. (b) A top view of the taper structure with different important design parameters. The green portion indicates the partially etched silicon with 150 nm height, while the orange portion indicates the full 220 nm height silicon section. TOx and BOx denotes the top oxide cladding and the bottom oxide layer of an SOI chip.

Considering the above, I propose an inverse taper edge-coupler as shown Figure 2.2. The taper begins with a tip of 150 nm by 150 nm cross section and then widens out in the lateral (horizontal) direction to match the 500-nm width of a standard single mode Si-waveguide. A second layer taper is then introduced at the end of the first taper section, $L_{1\text{Taper}}$ (see Figure 2.2-b), which also increases the taper height by an additional 70 nm, making the total height equal to 220 nm at the beginning of the second taper section, $L_{2\text{Taper}}$. Finally, by the end of the $L_{2\text{Taper}}$ section, the waveguide has cross-section dimensions of 220 nm by 500 nm for its height and width, respectively; which matches the dimensions of a single mode Si-waveguide on SOI wafer.

2.3 Numerical Analysis and Optimization

I used a 3D commercial full wave simulator based on the finite difference time domain (FDTD) method (Lumerical Solutions, Inc., n.d.) to optimize our proposed taper design. I used a conformal variant 1 mesh settings with accuracy level 3 and a PML (Perfectly Matched Layer) boundary condition in the simulations. Our design goal is to achieve high coupling efficiencies for both the TE and TM polarizations while keeping the taper dimension as small as possible. I used a fiber mode source in the full width half max (FWHM) wavelength span of 1500 nm to 1600 nm in our simulation with a 5 µm MFD to match the scenario of coupling light from a focused fiber to single mode Si-waveguide. I chose the total length of the taper ($L_{\text{Tot}}$) to be 30 µm, which is 10 microns
shorter than the one proposed in [11]. I optimized the $w_{\text{Trans}}$ (see Fig. 2) and the ratio of $L_{1\text{Taper}}$ to the total length ($L_{\text{Tot}} = L_{1\text{Taper}} + L_{2\text{Taper}}$), to maximize the coupling from a fiber tip with 5 $\mu$m MFD to a single mode Si-waveguide. Here the parameter $w_{\text{Trans}}$ is the transitional width of the bottom layer of the taper where the tip of the top layer starts as shown by the start of the orange colored layer in Figure 2.2-b. The optimized value of $L_{1\text{Taper}}/L_{\text{Tot}}$ was found to be 0.7 when $w_{\text{Trans}}$ is equal to 350 nm as shown in Figure 2.3.

Figure 2.3: Simulated fiber to TE mode coupling loss of the bilayer inverse taper coupler as a function of $w_{\text{Trans}}$ and $L_{1\text{Taper}}/L_{\text{Tot}}$.

Figure 2.4 shows the calculated coupling losses for the 30 $\mu$m long bilayer inverse taper for both TE and TM input polarizations. As the figure indicates, the coupling losses for TM mode at 1550 nm is 1.98 dB, whereas for the TE mode the loss is 1.01 dB. These performance characteristics make the proposed bilayer inverse taper a highly desirable edge-coupler device. As far as the overall device dimensions are concerned I should add that increasing the total length by 10 $\mu$m (i.e. $L_{\text{Tot}} = 40 \mu$m) reduces the TE coupling losses to 0.97 dB while decreasing the total length by 10 $\mu$m (i.e. $L_{\text{Tot}} = 20 \mu$m) increases the TE coupling losses to 1.4 dB for operation at 1550 nm wavelength. The TM coupling efficiencies follow the same trend as the TE coupling efficiency with the change of the total taper length. Since the improvement of coupling efficiency doesn’t scale at the same ratio as increasing the length I settled with the choice of 30 $\mu$m as the total length of the bilayer inverse taper.
Further analyses show that there is no significant cross coupling between the TE and TM modes due to the asymmetric bi-layer design. Figure 2.5 shows the extinction ratio of the power coupled to the TE0 mode to the power coupled to the TM0 mode for a TE input to the coupler. The similar extinction ratio of the power in TM0 mode to TE0 mode for a TM input is also included in the figure. This cross coupling is calculated in the waveguide section at the end of the coupler. The extinction ratio for both the cases stays above 25 dB in the wavelength window of 1500 nm to 1600 nm.
Investigations were also carried out to check the robustness of the taper design against fabrication imperfections. Here I present the results of the coupling efficiency calculations for the dimension variations of the taper tip. The original design dimensions of the taper tip are 150 nm for the width and 150 nm as well for the height. In the analysis, the taper tip height was varied from 100 to 200 nm and the taper tip width from 130 nm to 220 nm. Figure 2.6 shows the coupling efficiencies of the proposed bilayer inverse taper coupler as a function of the taper tip width and height for both TE and TM polarizations. For the TE input, the coupling efficiency is tolerant to the geometrical variations due to fabrication imperfections (i.e. ±30 nm variation in both height and width from a 150 nm by 150 nm square cross section) and stays close to the optimum value of -1.01 dB. For the TM mode, the coupling efficiency is minimally affected by the change in the taper tip width as evident in Figure 2.6-b where the color plot does not change in color in the horizontal direction. But it is more sensitive to the change in taper tip height which is demonstrated by the change in the color in the vertical direction in Figure 2.6-b. The optimum height for the taper tip turns out to be 170 nm (Figure 2.6-b). But I chose the taper tip dimension to be 150 nm for both the height and width to keep the symmetry and more importantly, maintain compatibility to commercial foundry rules.

The different sensitivities of TE and TM coupling efficiencies of the proposed bilayer inverse taper can be attributed to the geometrical shape of the TE and TM mode at the tip of the taper. Figure 2.7 shows the power profile of the TE and TM modes for a silicon waveguide of 150 nm height by 150 nm width buried in SiO$_2$ (as shown in Figure 2.1-b). As can be seen in Figure 2.7 for the TE mode, power sits mostly in the lateral direction and adheres to the sidewall of the waveguide while, for the TM mode the power is concentrated on the top and bottom wall of the waveguide.
Therefore, the TE mode, in principal, should be more sensitive to any change in the horizontal direction than the vertical direction while for TM mode the case is exactly opposite. But a change in waveguide width in the range under consideration does not affect the TE mode (Figure 2.6-a) because on an SOI platform the minimum waveguide width for a well confined single mode operation for Si-waveguides is 450 nm. In the range of waveguide widths under 180 nm, the TE modes are still loosely bound in the infinite horizontal plane of the SOI chip. But in the vertical direction the waveguide geometry is limited by the boundary of the top and bottom oxide layers (Figure 2.1-a). Hence, for the TM mode, being abundant in the vertical direction, the effect of the change of height of the waveguide is pronounced. Thus, the TM mode coupling efficiency is noticeably affected by the height change as can be seen in Figure 2.6-b. At this point, with the results of the performed analyses at hand, I proceed to the next sections describing the fabrication and characterization of the proposed bilayer inverse taper coupler.

![Simulated TE (left) and TM (right) mode profile at the taper tip of 150 nm width and 150 nm height on SOI wafer.](image)

2.4 Fabrication of the Bilayer Inverse Taper

The most challenging part in the fabrication process of the proposed bilayer inverse taper was the planning of the sample layout since cleaving the sample at the proper position is essential for carrying out a good characterization of the absolute coupling efficiency of the bilayer taper. For this purpose, I planned a specific approach with waveguides and tapers positioned at variable distances staggered with an offset of 200 microns from the edge of the sample. This approach will be explained later in the characterization section since the characterization calculations are related
to the sample layout and it would be more relevant explaining the layout along with the characterization setup. Here I discuss the fabrication steps for the bilayer inverse taper.

Fabrication of the bilayer inverse taper involves a two-step Si etch process on a SOI wafer— a partial Si etch of 70 nm etch-depth and a full etch of 220 nm. The process steps are shown in Figs. Figure 2.8-a and b. First, tungsten markers are fabricated on a piece of SOI wafer using e-beam lithography (Vistec EBPG 5000+). Then, using ZEP 520 positive resist, an opening was patterned to perform the partial etch (70 nm etch-depth). The partial etch of the Si layer was carried out using an Oxford Instruments Plasma Pro Estrelas100 DRIE System. In the next step, a negative resist (HSQ) was spun on the wafer and patterned to performed the full etch (220 nm) portion of the taper. Markers were used to properly align the layers and the full etched was carried out using the DRIE system. During this step, the 500-nm wide Si-waveguide which is attached to the end of the taper structure (also 500 nm wide) were also fabricated. The last step was the deposition of a 2 \( \mu \)m thick oxide (SiO\(_2\)) layer all over the sample which acts as the top cladding for the Si-waveguides. This deposition was done using a PECVD (plasma enhanced chemical vapor deposition) system (Oxford Instruments PlasmaLab System 100 PECVD).

Figure 2.8: (a) Top view schematics of the fabrication steps for the bilayer inverse taper including the metal alignment markers on the chip. (b) Fabrication steps of the bilayer inverse taper along the cross-sectional plane. The projection of only the front facet of the cross section at the plane is shown to avoid confusion.
Figure 2.9: a) Scanning Electron Micrograph (SEM) of one of the Bilayer inverse tapers on the fabricated sample. b) Same SEM in part-a with overlaid color for different height portions of the bilayer taper for visual aid.

Figure 2.9-a shows the Scanning Electron Micrograph (SEM) of one of the many bilayer inverse tapers fabricated on the sample under test. An overlaid color on the same SEM for visual aid is presented in Figure 2.9-b to distinguish between the two layers of the bilayer inverse taper.

Figure 2.10: a) bilayer inverse taper and b) reference inverse taper parameters as they were fabricated on the sample under test.

2.5 Sample Organization

In addition to the bilayer inverse taper, I also fabricated inverse taper designs as described in (Almeida, Panepucci, & Lipson, 2003). This was done to compare the performance of our taper with that of a conventional inverse taper fabricated under same conditions. In this chapter, I refer to the inverse taper by (Almeida, Panepucci, & Lipson, 2003) as the reference inverse taper. Figure 2.10 shows the dimensions of the fabricated bilayer (a) and reference (b) inverse taper on the sample side by side. Figure 2.11 shows a schematic of the chip layout, where the combined bilayer and reference inverse tapers are designated by letters M1, M2, and M3. Figure 2.11 also shows a set of standard Si-waveguide (220 nm height by 500 nm width) designated as M’. These Si-waveguides run the entire length of the chip, from edge-to-edge, and are used to measure the propagation losses associated with our Si-waveguides. The reason behind fabricating a reference
taper is to benchmark the performance of my fabricated bilayer taper against a popular inverse taper from literature which is also fabricated on the same platform using the same fabrication facilities so that a fair comparison can be made.

![Figure 2.11: Schematic diagram of the sample with three measurement groups of waveguides (M₁, M₂ and M₃). Each measurement group has a “reference inverse taper” (top) and a bilayer inverse taper (bottom) L_offset is the offset distance between each measurement group. The sample was cleaved at the distance L_cleave from the left edge of the wafer. The right edge was cleaved abruptly, so all the waveguides terminated at the edge. M' at the top is the group of facet cleaved waveguides for propagation loss measurement.](image)

One of the major challenges in the measurement process is the cleaving of the chip at a proper position with high enough precision so that the edge of the cleaved chip and the taper facets coincide. Such accurate cleaving is necessary for optimum coupling, but is very difficult to achieve even with high precision cleaving instruments. Laser assisted cleaving (CMC Microsystems, Canada, n.d.), deep trench cleaving (Yap, et al., 2006) different techniques to achieve high precision cleaving. To confirm the measured coupling efficiency of the bilayer taper I fabricated several experimental sets of waveguides where the start position of the waveguides was staggered in 200 µm increments (L_offset). I used a laser assisted setup to create cleaving mark on the SOI sample with microscope aided positioning system with an accuracy of ~ 10 µm. Using an Nd-Yag laser beam I drew a laser cleave mark on the sample edge to determine the cleaving position so that the edge of the sample lies as close as possible to the tip of the bilayer taper. Then the sample was cleaved along the crystalline line running through the cleave mark. In the resultant sample the edge was 30.76 µm away (L_cleave) from the tip of the nearest waveguide group. Light traverses this distance L_cleave partially through both the top and bottom oxide layer to reach the front facet of the
tip of the taper before coupling. With this setup equations of loss calculation can be constructed for the waveguides in each of the measurement sets value of power loss \( P_{ox} \) due to propagation through the offset distance in the SiO\(_2\) layer between the cleaved edge of the chip and the taper facets can be extracted. The knowledge of \( P_{ox} \) is necessary to calculate the absolute coupling efficiency of the bilayer inverse taper. The waveguide set \( M' \) (above \( M_1 \) in Figure 2.11), which was initially connected to a bilayer and “reference inverse taper”, terminates at the left and right edges running through the full length of the chip. The power measurement from the waveguide set \( M' \) facilitates the Fabry Perot measurement of the propagation loss through the waveguides fabricated on the chip.

![Diagram of laser assisted cleaving](image)

*Figure 2.12: Schematic diagram of laser assisted cleaving of the fabricated sample. The different waveguide groups are shown by solid lines staggered in position.*

### 2.6 Measurement Setup and Results

I have characterized the performance of our bilayer inverse taper under two scenarios: a) free space coupling, which allows us to carefully control the polarization of the input optical field; and, b) using a focused SMF, with 5 \( \mu \)m MFD, which is a more common approach in industry. Figure 2.13-a, and Figure 2.13-b show schematics of the two scenarios. With a free space coupling setup (Figure 2.13-a) the absolute coupling efficiency of the taper (both bilayer and reference inverse taper) is dependent on the incoming mode size from the input objective lens, in other words the power of the input objective lens. But a control over the polarization of the input beam can be easily achieved by using polarization optics components in the beam path of a free space Gaussian
beam. Hence, I used the free space coupling setup in Figure 2.13-a for comparative measurements of the performance of the bilayer taper over the reference inverse taper for both TE and TM polarizations. The input objective lens used for the free space coupling is a Newport F-L40B (40X magnification) long working distance lens and for collection at the output, a Newport M-40X objective lens with 0.65 mm working distance was used in the setup in Figure 2.13-a. Due to the unavailability of a polarization controlled lensed fiber, I used a single mode lensed fiber (TSMJ-3U-1550 by Oz Optics) with 5 µm MFD in the fiber coupling setup (Figure 2.13-b) to calculate the absolute coupling efficiency of the bilayer inverse taper.

![Diagram of measurement setups](image)

*Figure 2.13: Measurement setups for, (a) a free space coupling using objective input lens, (b) a focused single mode fiber input with 5 µm MFD.*

Using the free space coupling scheme (Figure 2.13-a) and a Thorlabs broadband diode source in telecom wavelengths (C-band), for the TM mode, I measured an output power of 68.90 µW for our inverse bilayer taper as compared to an output power of 47.52 µW for the “reference inverse taper,” at the detector. This represents a 1.61 dB improvement in coupling efficiency for our bilayer
taper. Using the same setup, for the TE mode, I measured an improvement of 1.91 dB in coupling efficiency for our bilayer taper as compared to the “reference inverse taper”. Table 2.1 summarizes the improvement in coupling efficiencies achieved by the bilayer inverse taper over the reference inverse taper for both TE and TM mode coupling.

<table>
<thead>
<tr>
<th>Improvement for Free Space Coupling (TE)</th>
<th>Improvement for Free Space Coupling (TM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.91 dB</td>
<td>1.61 dB</td>
</tr>
</tbody>
</table>

*Table 2.1: Improvement of coupling efficiency by Bilayer inverse taper over the reference inverse taper.*

I now return to the second measurement setup shown in Figure 2.13-b; i.e. the focused SMF excitation. Continuing with the comparative measurements, I have observed an improvement of approximately 1.48 dB in the coupling efficiency for our bilayer inverse taper as compared to the “reference inverse taper”. Using an Agilent optical spectrum analyser (OSA), I have also compared the spectra of our bilayer inverse taper with that of the “reference inverse taper.” Results are shown in Figure 2.14 obtained using the setup in Figure 2.13-b (replacing the detector by the Agilent OSA). The comparison shows a consistent improvement of the coupling efficiency for the bilayer inverse taper over the “reference inverse taper,” over a wavelength window of 50 nm. Here, our measurement is limited by the bandwidth of the available source. I expect the bilayer inverse taper coupler to demonstrate a broader bandwidth like the calculated spectrum shown in Figure 2.4.

![Figure 2.14: Measured spectral responses of the bilayer inverse taper and the reference inverse taper. Light was coupled from a non-polarization maintaining lensed fiber of 5 μm mode field diameter.](image)

As discussed earlier, using the setup in Figure 2.13-b, I can also ascertain the absolute coupling efficiency – or the coupling loss – associated with the bilayer taper for the fiber coupling case. To
do so, I needed to measure and compensate for: propagation losses in the Si-waveguide section, the reflection and diffraction losses ($P_{ox}$) associated with propagating through the distance $L_{cleave}$ in the SiO$_2$ (Figure 2.11) between the chip edge and taper facet, and Si-waveguide out coupling losses. Below is a more elaborate discussion of the detailed measurement and calculation process to extract the absolute coupling efficiency ($P_c$) of the bilayer inverse taper.

As the first step to calculate the coupling loss ($P_c$), I measure the output of two BI (Bilayer Inverse) taper waveguides from two adjacent waveguide groups ($M_1$ and $M_2$) as shown in Figure 2.11. These two waveguide sets differ by the length $L_{offset}$ in total length. Two different loss equations are constructed for each of the BI taper waveguides from each set ($M_1$ and $M_2$). I solve these equations to obtain the propagation loss per mm ($P_{ox}$) through the SiO$_2$ region (marked by $L_{cleave}$ and $L_{offset}$ in Figure 2.11). The equations are as follows:

For the BI taper waveguide in group $M_1$

$$L_{cleave}P_{ox} + (L_{tot} - L_{cleave} - L_{taper})P_{prop} = P_{tot-M_1} - C \quad (2.1)$$

For the BI waveguide in group $M_2$

$$(L_{cleave} + L_{offset})P_{ox} + (L_{tot} - L_{cleave} - L_{offset} - L_{taper})P_{prop} = P_{tot-M_2} - C \quad (2.2)$$

where,

$$C = P_c + P_{facet-lens} + P_{refl-ox} \quad (2.3)$$

The symbols in the above equations are defined as follows:

$L_{cleave}$ = Distance of the taper tip to the edge of the cleaved sample for the waveguide set nearest to the edge.

$L_{offset}$ = Distance between the tips of the two adjacent waveguide sets

$L_{tot}$ = Total length of the sample

$L_{taper}$ = length of the BI taper = 30 micron
$P_{ox}$ = Power loss per mm due to propagation through the SiO$_2$ region between the sample edge and the tip of the taper

$P_{prop}$ = Power loss per mm due to propagation through the Si-waveguide

$P_{tot-M_1}$ = Total power loss measured at the output of the BI taper waveguide in the group M$_1$

$P_{tot-M_2}$ = Total power loss measured at the output of the BI taper waveguide in the group M$_2$

$P_c$ = coupling loss of the BI taper

$P_{facet-lens}$ = Out coupling loss from the right edge of the waveguide (also the sample) through the output objective lens

$P_{refl-ox}$ = Fresnel reflection loss at the left facet between the air and oxide, approximated by the oxide-air Fresnel reflection loss.

I obtain the $P_{prop}$ from the Fabry Perot measurement of the waveguides group M' which runs through the total length $L_{tot}$ of the sample. Measurements of all the lengths mentioned above are carried out using scanning electron micrograph of the fabricated sample. Now this is a two-equation system with two unknown parameters ($P_{ox}$ and $P_c$). Solving the system of equations above I obtain the value of the coupling loss ($P_c$) of the BI taper. At the excitation wavelength of 1550 nm, these losses were measured to be 2.4 dB (propagation loss in the Si waveguide section), 3.21 dB (Loss due to propagation through the oxide section), and 2.03 dB (end facet out-coupling loss). Using these results, I estimated the coupling loss of our bilayer inverse taper at the excitation wavelength of 1550 nm is 1.7 dB – when light is fed to the taper using a SMF with 5 μm MFD. Such 1.7 dB coupling loss of the taper section ($P_c$) has two contributing factors: first, the loss due to coupling into the taper and the reflection from the transitional region of 150 nm height to 220 nm. And, second, the Rayleigh scattering losses from the rough sidewalls of the taper due to fabrication imperfection. The first kind of these losses is an inherent property of the taper structure and will be present in any such bilayer inverse taper. However, the losses due to fabrication roughness (the second) can be reduced by using better cleanroom facilities and more fine-tuned recipes, which will reduce the Rayleigh scattering loss resulting in a coupling loss lower than 1.7 dB.
2.7 Performance Benchmarking

Table 2.2, below, summarizes and compares the results for our proposed bilayer inverse taper with other inverse taper edge-couplers in the literature. A survey of the results shows that for the given MFD (5 μm in our case), our proposed bilayer taper is the shortest edge-coupler with insertion loss of only 1.7 dB, while keeping the fabrication and device geometry simple (for example, no need for complex undercut cantilever as in Ref. [ (Wood, Sun, & Reano, 2010)]). The fabricated taper already demonstrated ~1.5 dB improvement over the reference inverse taper [ (Almeida, Panepucci, & Lipson, 2003)] fabricated on the same sample using the same fabrication facilities at TNFC (Toronto Nano-Fabrication Center). I should also add that in the case of our bilayer inverse taper, the partial etch-depth of 70 nm (i.e. 150 nm Si height) was chosen so it is compatible with the standard partial etch-depth and design rules allowed by the commercial foundries.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Taper length</th>
<th>Input MFD</th>
<th>Loss (dB)</th>
<th>Tip Width</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pu, Liu, Ou, Yvind, &amp; Jørn, 2010)</td>
<td>300 μm</td>
<td>2.9 μm</td>
<td>0.66 dB (TE) 0.36dB (TM) 0.3 dB (Fiber)</td>
<td>40 nm</td>
<td>Oxide taper and polymer over layer</td>
</tr>
<tr>
<td>(Chen, Doerr, Chen, &amp; Tsung-Yang Liow, 2010)</td>
<td>300μm</td>
<td>Cleaved fiber</td>
<td>1.5-2 dB 1dB Polarization Dependent Loss (PDL)</td>
<td>80 nm</td>
<td>Cantilever</td>
</tr>
<tr>
<td>(Fang, et al., 2010)</td>
<td>150 μm</td>
<td>Focused/ Cleaved</td>
<td>1.7-2dB/3.8dB (TE) 2.9-3dB/4dB (TM)</td>
<td>150 nm</td>
<td>Oxide cantilever, beam, undercut</td>
</tr>
<tr>
<td>(Galán, Sanchis, Sánchez, &amp; J. Martí, 2007)</td>
<td>400 μm</td>
<td>Cleaved</td>
<td>3.5 dB (TE) 3.7dB (TM)</td>
<td>200 nm</td>
<td>V groove and cantilever</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>Width</td>
<td>Insertion Loss</td>
<td>Cladding</td>
<td>Process Complexity</td>
</tr>
<tr>
<td>----------------------</td>
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<td>----------</td>
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</tr>
<tr>
<td>(Wood, Sun, &amp; Reano, 2010)</td>
<td>7.5 μm</td>
<td>1.5 μm</td>
<td>&lt;1 dB (TE) &lt;1dB (TM)</td>
<td>60 nm</td>
<td>Undercut/ Cantilever Difficult Fab</td>
</tr>
<tr>
<td>(Bakir, et al., 2010)</td>
<td>200-300 μm</td>
<td>3 μm</td>
<td>&lt;1dB (TE) &lt;1dB (TM)</td>
<td>80 nm</td>
<td>Oxide injector cladding waveguide</td>
</tr>
<tr>
<td>(Cardenas, et al.)</td>
<td>100 μm</td>
<td>5 μm</td>
<td>0.7 dB (Fiber)</td>
<td>160</td>
<td>Simple waveguide taper</td>
</tr>
<tr>
<td>(Almeida, Panepucci, &amp; Lipson, 2003)</td>
<td>40 μm</td>
<td>5 μm</td>
<td>&gt;3dB (Fiber)</td>
<td>100 nm</td>
<td>Simple waveguide taper</td>
</tr>
<tr>
<td>Bilayer Inverse Taper</td>
<td>30 μm</td>
<td>5 μm</td>
<td>1.7 dB (Fiber) 1dB polarization dependent loss</td>
<td>150 nm</td>
<td>SOI edge</td>
</tr>
</tbody>
</table>

Table 2.2: Comparison of the bilayer taper performance with other inverse taper designs in literature.

### 2.8 Conclusion

I have presented the design, fabrication, and experimental demonstration of a compact and low loss bilayer inverse taper edge-coupler for Si-photonics circuits. The proposed bilayer taper shows enhancements in free space to waveguide coupling efficiencies, for both the TE and TM modes, of more than 1.5 dB as compared to the conventional inverse taper coupler from ref. (Almeida, Panepucci, & Lipson, 2003). Also, the bilayer inverse taper demonstrates a similar enhancement in coupling efficiencies for the case of fiber to Si-waveguide coupling: i.e. the coupling loss is approximately 1.7 dB when a focused SMF (with 5 μm MFD) is used to couple the light into the Si-waveguide. The proposed edge-coupler is simple to fabricate, it is only 30 μm long, and the device geometry and dimensions conform to the standard design rules for Si foundries.
Chapter 3. Broadside High Index Dielectric Beam Routing

In the previous chapter I discussed the bilayer inverse taper coupler and its application to efficiently couple light to silicon (Si) photonic chip from an external source. But in hybrid photonic platforms such as Si/Al-GaAs/InP, there are other coupling problems which must be addressed, for example, on-chip sources can be vertical cavity surface emitting lasers (VCSELs) bonded with a Si wafer. The design and easy fabrication of a vertical via structure is essential to for such integrated VCSEL systems since vertical light should be converted to horizontal beams to couple to the planar photonic components. Furthermore, the lack of a seamless fabrication process of CMOS and Si-photonics on a same platform makes it necessary to establish an efficient chip-to-chip interconnect systems. In this chapter, I propose a technique to control the direction of a beam using a dielectric optical micro-prism structure by properly designing its geometry. It is shown that by selectively choosing the slope of a high-index micro prism, the direction of the radiated beam from the tip can be controlled in the broadside direction of the prism structure. An easy fabrication method to integrate such broadside beam routers on a Si platform has also been demonstrated. Additionally, a technique to build the beam router on an elastic PDMS platform which can facilitate a stress induced beam scanning in the broadside has been demonstrated. This specific feature of beam direction control can find application in free space optical interconnects, plasmonics, solar cells and optical sensing.

3.1 Introduction

Delivering light to the nano-photonic components in an optical system by controlling the spatial dynamics of light has been a topic of wide interest in the field of nano-photonics. Plasmonic nano-antenna [ (Gramotnev & Bozhevolnyi, 2010)], multilayer metal-dielectric stacks [ (Kotynski, Stefaniuk, & Pastuszczak, 2011)] or metal slot waveguides [ (Chen, Shakya, & Lipson, 2006)] have been investigated as techniques to confine light in subwavelength dimensions. Stockman et al. have proposed a technique of localizing the optical energy in a small part of a nano-system by means of coherent control [ (Stockman, Faleev, & Bergman, 2002)]. Maksymov et al. demonstrated optical beam steering by 3D Yagi-Uda like metal nano-antenna array [ (Maksymov,
Staude, Miroshnichenko, & Kivshar, 2012). Volpe et al. has proposed a subwavelength spatial phase control method to reconfigure the optical near field distribution near plasmonic nanostructures [Volpe, Cherukulappurath, Parramon, Terriza, & Quidant, 2009]. Furthermore, the control over the flow of optical energy has been proved to be useful in diverse fields such as photodetection [Tang, et al., 2008], (Gonzalez & Boreman, 2004], photovoltaics [Atwater & Polman, 2010], nano-imaging [Betzig, 1995] and single photon emission [Kinkhabwala, et al., 2009]. In most these applications, the antennae were constructed based on the plasmonic properties of metal. The collective electron oscillation influenced by the interaction of an electromagnetic wave with metal introduces the antenna-like properties to the metallic nano-structures (i.e. nano-particles or bow tie structures). The control over the emission direction thus can be achieved by controlling the optical phase, or the geometric parameters of the metal nano-structures. However, one drawback of optical field control using metallic nano-structures is the Joule heating of the metal and the concomitant optical loss. Dielectric beam routing structures have been proposed by several researchers in literature. Xue et al. have studied intra-chip free space communication using dielectric overhead micro lenses and mirrors to establish communication between different parts of the chip on a GaAs chip integrated with silicon photonics [Xue, et al., 2010]. Gu et al. have demonstrated use of high index polymer surface couplers and integrated GaAs/AlAs multiple quantum-well devices directly onto Si chip [Gu, Nair, & Haney, 2013.]. Chronis et al. have utilized the angled Si wet etch property of KOH to deflect a vertical beam to excite SPP by total internal reflection [Chronis & Lee, 2004]. Also, Chao et al. has used total internal reflection at the facet of an angle polished fiber to couple to Si photonic chip through a grating coupler [Li, et al., 2014].

In this chapter, I show that by controlling the slope of a high index dielectric, non-adiabatic tapered micro prism structure, a control over the direction of the beam released from the prism can be directed to the broadside direction. Furthermore, a control over the beam direction can be achieved by controlling the slope of the prism structure. I also present an experimental demonstration of the broadside beam routing by a Si micro-prism on a silicon wafer. Furthermore, I have used Polydimethylsiloxane (PDMS) to build a stretchable micro-prism which facilitates a beam scanning in the broadside direction at the 1550 nm wavelength regime upon application of lateral stress. Since, PDMS is also a transparent high index material (as compared to air) in the visible wavelengths, such beam scanning can also be achieved in the visible regime. This technique of
beam direction control can be very useful in different applications of nano-photonics such as free space interconnects, surface plasmon polariton (SPP) mode excitation in the visible wavelengths, guiding of light in the active layers of photovoltaic cells, plasmonic sensors, nonlinear signal conversion and photon detection.

The rest of the chapter is organized as follows: in the next section I discuss in detail – the beam routing mechanism utilizing the total internal reflection inside a high index micro-prism. Then I discuss about the fabrication and measurement of the Si micro-prism for broadside beam routing. Next to that, I discuss about the fabrication process of the PDMS beam scanning micro-prism and the measurements of the stress induced beam scanning using the PDMS micro-prism.

3.2 Beam Routing Mechanism

In a prism submerged in a low index medium (i.e. air), as light is incident at one of its lateral facets from inside its high refractive index medium at an angle larger than the critical angle (between the prism material and air), a total internal reflection occurs and light is reflected back into the high index medium (as depicted in Figure 3.1). Per Snell’s law, the angle of reflection equals to the angle of incidence. The final direction of the reflected beam upon incidence on any of the other facets of the prism is dependent on the geometry and the refractive index of the prism as well as the surrounding medium. Since I aim to device a beam routing system compatible with integrated Si-photonics, I choose a Si micro-prism structure with a sidewall angle of 54.7° as depicted in Figure 3.1. The reason behind the choice of the inclination angle is since a KOH wet etch of a masked <100> Si wafer creates a sidewall angle of 54.7° as the Si is etched down from the edge of a mask pattern. Adopting this fabrication process to achieve a fixed prism angle of 54.7° as shown in Figure 3.1 helps get rid of any grey scale lithography to manually control the slope of the etched sidewall of the micro-prism structure. Figure 3.1 depicts the routing of a beam upon total internal reflection from one of the slanted facets of a prism with the prism angle of 54.7°. Due to the 54.7° inclination, the angle of incidence of the beam in the first slanted wall of the prism (shown by the yellow arrow in Figure 3.1) is 54.7° and the angle of incidence of the second slanted wall of the prism (depicted by the angle ABO in Figure 3.1) is 15.9°. The angle that the beam is released from the prism (θ_{rl-air} in Figure 3.1) depends on the refractive index of the surrounding medium as well as the prism angle. Considering the surrounding medium as air, the angle that the beam escapes from the prism (θ_{out-air}) with respect to the normal direction of the surface can be
calculated from the Snell’s law to be $70.46^\circ$. This released beam makes an angle ($\theta_{rl-air}$) of $35.16^\circ$ with the horizontal direction as shown in Figure 3.1. Changing the surrounding medium to be oxide (refractive index 1.44) the released beam can be made almost horizontal ($\theta_{rl-oxide} = 6.2^\circ$).

![Figure 3.1: Ray Diagram of beam routing in a Si prism of 54.7\(^\circ\) slope](image)

\[
\begin{align*}
AOB &= 109.4^\circ \\
ABO &= 15.9^\circ \\
\theta_{rl-air} &= \sin^{-1}(\sin 15.9^\circ \times \eta_{Si}) \\
&= 70.46^\circ
\end{align*}
\]

In the practical case of such a Si micro-prism being illuminated from the bottom, the beam diameter is typically comparable to the base of the Si prism. Therefore, although the routing mechanism remains like the one discussed above, the directionality of the released beam depends on the position of the input beam with respect to the center of the base of the micro-prism. I used a commercial-grade simulator based on the finite-difference time-domain (FDTD) method to simulate the beam routing through a micro Si prism as discussed above (Lumerical Solutions, Inc., n.d.). Figure 3.2(a) and Figure 3.2(b) show the power density plot of unidirectional beam routing using a Si micro-prism submerged in air and SiO\(_2\) respectively. As evident from the figures, a shifted beam towards the left results in much of the power in the beam to be routed towards the opposite (right) side of the prism and is released into the surrounding medium in the direction determined by the Snell’s law. Figure 3.2(c) shows the power density distribution of a beam traversing through such a Si micro-prism with a centered beam configuration with SiO\(_2\) as the surrounding medium. In this case, the finite width of the beam results in being incident partially on both the slanted walls of the micro-prisms. Thus, the beam is partially directed towards both the sides of the prism following the same rules of reflection and refractions and gets released in the surrounding lower indexed medium.
3.3 Fabrication

Fabrication of the Si micro-prism structure is straightforward and requires a single step lithographic process. First, a <100> Si wafer is thermally oxidized to produce a 300-nm thick oxide for 18 min in a Bruce Technologies Inc. furnace. Next, ma-N 2405 negative resist was spun on the oxide layer and the resist was patterned as a single 500 nm wide and 5 mm long line using the Vistec EBPG5000+ electron beam (Ebeam) lithography unit at the Toronto Nano-Fabrication Center TNFC) (step 3 in Figure 3.3). This is the only lithographic step in making the Si micro-prisms. After development of the exposed resist, an oxide etch was carried out using the Oxford Instruments PlasmaPro Estrelas100 DRIE System. As the next step, I prepared a 45% KOH solution and heated it up to a stabilized temperature of 80°C. Then the <100> Si sample with patterned oxide mask was submerged into the 45% KOH solution on a Teflon holder for 25 mins. The etch rate of the prepared solution was slightly less than 1 μm/min; therefore, after the 25 min etch I obtained a Si prism of 20 μm height which translates to a base size of 28.32 μm, as depicted in the schematic fabrication process diagram in Figure 3.3. For reducing diffused reflection at the back surface of the sample while coupling light during the characterization experiment (described in section 3.4), I carried out chemical-mechanical polishing of the back plane to achieve a smooth surface (~20 nm average roughness).
Figure 3.3: Fabrication process of the Si micro prism. The backside polishing step using CMP at the end is not shown in the figure.

3.4 Beam routing experiment

For the characterization of the fabricated sample, I built a radiation pattern measurement setup with the sample attached at the center of a rotational stage (Figure 3.4(b)). Since the wavelength of interest for this experiment is the telecom wavelength (1550 nm), I used a JDS Uniphase SW515101 Tunable Laser diode source tuned to emit at a center wavelength of 1550 nm. From the source, light was carried through a single mode fiber to the characterization table and converted to a free space Gaussian beam using a fiber collimator lens. The Gaussian beam was focused at the base of the Si prism as shown in Figure 3.4(a) using an objective lens (Newport F-L40B). The beam was focused following the shifted beam topology as mentioned in section 3.2 to achieve unidirectional beam routing. Then the radiation pattern was measured using the Newport 818-IR detector attached to the rotating arm of the rotation stage (Figure 3.4(b)).
Figure 3.4: (a) Schematic diagram of the sample with the Si micro-prism. The red arrows indicate the routing of the beam. (b) Experimental setup for radiation pattern characterization.

The red dashed curve in Figure 3.5 shows the measured radiation pattern of the Si micro-prism and compares to the simulated results plotted by the green solid curve. It is evident from the figure that the measured radiation pattern closely matches the theoretically predicted pattern.

Figure 3.5: Comparison of simulated (green solid) and measured (red dashed) radiation pattern in the broadside direction using the Si micro-prism.

3.5 PDMS Micro-Prism for Beam Steering

As described in the previous section, for the broadside beam routing through the micro-prism, the angle of release ($\theta_{rl-air}$ in Figure 3.1) of the out-coming beam is solely dependent on the slope of the sidewall of the deflecting prism. Therefore, a control over the direction of the released beam is achievable if the slope of the micro prism can be arbitrarily controlled. For such purpose, naturally, a solid Si micro-prism like the one described in the previous sections is not an ideal choice. Instead, an elastic material with a relatively higher index than air, for which, the absorption of light is negligible would be appropriate for the purpose. Cured PDMS is an elastic polymer and has a refractive index of 1.4 and is transparent at visible and near infrared wavelengths. Hence, I chose PDMS to be the material to fabricate our beam scanning micro-prism structure effective in both infrared and visible wavelengths. Our aim was to apply lateral stress on a PDMS micro-prism and
change the sidewall slope which can facilitate scanning of the deflected beam in the broadside direction.

To fabricate the PDMS micro-prism I first used a Si substrate to etch a V shaped groove of 20 \( \mu m \) depth which is then used as a mold to shape the surface of a PDMS film using a pattern transfer method. Figure 3.6 shows the schematic of the steps of fabricating the PDMS micro-prism structure on a PDMS film. Once again, I started the fabrication process by acquiring a piece of a thermally oxidized \(<100>\) Si wafer (as mentioned in the previous section). The size of the oxidized Si sample was of a regular microscope glass slide. I then spun a positive resist (ZEP 520) compatible to electron beam lithography on the oxidized surface of the sample. Next, using the same Vistec EBPG5000+ Ebeam unit at the TNFC facilities I patterned a rectangular opening in the resist layer with the dimensions of 28.32 \( \mu m \) width and 5 mm length. As the next step, I did a DRIE etching (PlasmaPro Estrelas100 DRIE System) such that the oxide mask layer on the Si sample gets etched out in the region of the patterned opening in the resist layer. Then I ran the wet KOH etching of the sample with a 45\% KOH solution at 80\(^\circ\) C temperature for ~ 25 mins. The KOH etch starts etching the exposed Si in the opening area of the oxide mask on top of the \(<100>\) Si substrate creating the side walls at the characteristic 54.7\(^\circ\) angle. At this point (step 5 of Figure 3.6) I got our mold ready for patterning the PDMS.
I used a SYLGARD 184 SILICONE ELASTOMER kit from Dow Corning Corporation to prepare a flexible PDMS film with the micro-prism on the top surface of the film. I prepared a 10 to 1 mixture of the two liquids in the package as suggested by the Dow Corning data sheet and applied the viscous mixture on top of the prepared Si substrate containing the V groove in a petri dish. I prepared enough mixture so that the thickness of the liquid mixture after applying on the Si substrate was ~ 1mm. Then I put the petri dish along with the applied PDMS and the Si mold in a vacuum chamber for 45 minutes to get rid of the bubbles from inside the liquid PDMS. After the vacuum treatment, the petri dish was kept in an oven at a temperature of 70°C for 1.5 hours for the curing of the PDMS. After curing the PDMS solidified and created a transparent elastic film on top of the Si substrate which contained, on its surface that is in contact with the top surface of the Si mold, the inverse features initially patterned on the top surface of the Si substrate. Next, with a sharp scalpel the thick PDMS film cut around the Si substrate. Then the substrate mold was separated along with the PDMS film on top of it from the petri dish. At this point the PDMS film was cut again in a rectangular shape along the edges of the Si mold such that the cut-lines fall inside the edge of the Si mold. Then, starting from a corner, the cured PDMS film was carefully peeled off from top of the Si substrate. Thus, the PDMS film that contains a micro-prism on its top
surface embossed by the v-shaped groove in the top surface of the Si substrate mold (steps 7 and 8 in Figure 3.6) was obtained.

### 3.6 Beam scanning measurement

Figure 3.7(b) shows the experimental setup for the measurement of the stress induced beam scanning using the PDMS micro-prism sample. I used a PELCO Large Universal Vise Clamp as a stretchable center stage to hold the stretchable PDMS film perpendicular to the input beam in the measurement setup depicted in Figure 3.7(b). The PELCO stage can apply lateral stress to the PDMS film. Such lateral stress expands the base size of the PDMS micro-prism structure as depicted in Figure 3.7(a). Such stress induced expansion of the base of the PDMS micro-prism changes the inclination of the sidewalls of the prisms. From the discussion in section on the Beam Routing Mechanism, such a change in the sidewall inclination results in a change in the direction of the deflected beam ($\theta_{\text{ft-air}}$) by the micro-prism. Due to the physical structure of the PELCO clamp used to introduce stress on the PDMS sample, it was required to use a single mode fiber to deliver the light from the JDS Uniphase diode laser source to the base of the PDMS micro-prism instead of coupling through an objective lens as depicted in Figure 3.4-b. The PELCO clamp stage allowed to gradually increase the stress on the PDMS film from zero deformation to a maximum limit before tearing off the PDMS film.

![Figure 3.7: a) Schematic of the PDMS film with the micro-prism being expanded with different lateral stresses. The yellow arrows depict the input beam and the change of deflected beam directions due to stress. b) Schematic of the beam scanning measurement setup.](image-url)
Figure 3.8: a) Simulated radiation pattern of PDMS micro-prism. Red solid curve shows the radiation pattern for a PDMS micro-prism with prism angle of 54.7° while green solid curve shows the changed radiation pattern due to stress. b) Measured radiation pattern of the fabricated PDMS micro-prism corresponding to the stress and no stress case in (a). The prism angle for no stress condition is 54.7° while with stress the angle reduced to 51.6° due to enlargement of the prism base because of stress.

Figure 3.8 presents the change in the deflected beam direction as a function of the broadside angle due to the expansion of the prism base because of the change in applied lateral stress. The solid curves (Figure 3.8-a) represent the radiation patterns calculated by Lumerical FDTD (Lumerical Solutions, Inc., n.d.) while the dashed curves (Figure 3.8-b) represent the corresponding measured data at three different stress levels. The method used to estimate the applied pressure to create the stress is described in section 3.7. The evident conformity between the simulated and the measured radiation pattern confirms effectivity of the mechanical beam scanning concept using the mechanically stretchable PDMS film.

### 3.7 Stress Estimation for Beam Scanning

The required strain level to achieve beam scanning, in the method described above, was calculated using the stress-strain relation given by the Young’s modulus of PDMS. The values of Young’s modulus for the PDMS film was obtained from an earlier work by Johnston et al. in 2014 (Johnston, McCluskey, Tan, & Tracey, 2014). The rigidity of the PDMS film depends significantly on its curing temperature. Figure 3.9 shows the PDMS Young’s Modulus as a function of curing temperature. Furthermore, the amount of force needed to create specific amount of lateral deformation to achieve the change in the slope-angle of the PDMS prism also depends on the length of the PDMS film (with no stress applied) and its cross-sectional area. The following equation was used to calculate the force required to create desirable deformation in the base size of the micro-prism on the PDMS film:

\[
\text{pressure} = \frac{F}{A} = \frac{YA\Delta L}{L_0}, \quad (3.1)
\]
where, $F$ is the applied lateral force, $A$ is the cross sectional area of the PDMS film (Figure 3.7-a), $Y$ is the Young’s Modulus of PDMS, $\Delta L$ is the lateral deformation of the film and, $L_0$ is the initial length of the film in the direction of pressure (Figure 3.7-a).

![Graph](image)

Figure 3.9 Dow Corning Sylgard 184 (PDMS) Young's Modulus vs curing temperature. Figure obtained from (Johnston, McCluskey, Tan, & Tracey, 2014).

In the experiment, as mentioned in section 3.5, during the PDMS film preparation, the curing was carried out at a temperature of $70^\circ$ C. Therefore, in the stress calculation, from Figure 3.9, the Young’s modulus for the PDMS film was chosen to be 1.8 MPa. However, per equation 3.1 above, the lateral force required to create a specific length-deformation of the PDMS film will vary depending on the length and cross-sectional area of the PDMS film. Hence, the calculated force will vary from film-to-film since the film sizes varied from sample-to-sample. To avoid inconsistencies in the calculated stress, lateral pressure (force per unit cross sectional area) was calculated. Additionally, the pressure required to achieve desirable deformity was calculated for unit length of the PDMS film ($L_0 = 1$ m).
Figure 3.10 shows the beam radiation directions (obtained by simulation in Lumerical FDTD) at different lateral pressure levels applied on the PDMS film. The pressure levels corresponding to the specific beam routing directions achieved in the experiment (indicated in Figure 3.9) were also calculated using the approach discussed above.

3.8 Conclusion

To summarize, in this chapter I introduced a concept of beam routing using an integrated micro-prism on a <100> Si chip utilizing the total internal reflection inside a Si prism. I fabricated the proposed Si micro prism and demonstrated beam routing in the broadside direction. I then extended this beam routing concept to a flexible PDMS platform and demonstrated beam scanning in the broadside direction by applying lateral stress to the PDMS micro-prism. The proposed beam routing scheme can find potential applications in inter-chip optical communication for integrated photonics and act as a vertical via for multilayer photonic circuitry. The demonstrated PDMS beam scanning technique can be useful in exciting surface plasmon polaritons at a metal/dielectric interface in visible wavelengths with significantly high efficiencies – hence can be useful for SPP sensors where an angular change in illumination direction needs to be measured.
Chapter 4. An Efficient Surface Plasmon Excitation Scheme

In the previous chapter I have introduced the broadside beam routing and scanning method using silicon (Si) micro prism structure and an elastic PDMS micro-prism structure respectively, utilizing the total internal refraction of light in the internal wall of the prism structure. A KOH etch of <100> silicon (Si) was used to fabricate the Si micro prism structure while a KOH etch Si mold was used to fabricate the elastic PDMS micro-prism structure by pattern transfer method. With the KOH wet etch of Si, the achievable slope is limited to $54.7^0$. In this chapter I present a new technique of exciting a surface plasmon polariton mode at an Au/SiO$_2$ (gold/glass) interface using a KOH etched Si-tip structure with very high efficiency. The detailed design technique and the geometrical optimization of the SPP excitation scheme as well as the fabrication process and the characterization of the sample device is presented in this chapter.

4.1 Introduction

Surface plasmon polaritons (SPP) are the propagation of electromagnetic wave coupled with a collective electron oscillations and confined along a metal-dielectric interface (Maier S. A., 2007). Due to the subwavelength nature and high spatial confinement the SPP mode sizes can reach beyond diffraction limit. Hence, for confining light in the smallest possible dimensions SPPs are naturally a very convenient choice (Maier S. A., 2007). Thus SPPs have found applications in many emerging areas of nano-photonics such as integrated optics [(Charbonneau, Lahoud, Mattiussi, & Berini, 2005), (Kik, 2007)], field enhancement (Maier S. A., 2006), sensing (Ming Li, 2015) and imaging [(O. Mitrofanov, 2015), (Simon Forest, 2016)]. Advancements have also been made to improve the directionality of an excited SPP mode [(Anders Pors M. G.-C., 2014), (Xiushan Xia, 2015), (Jing Yang, 2014), (Jiao Lin, 2013), (Wenjie Yao, 2015)]. However, an efficient excitation of the SPP mode from the source is of high importance for nano-photonic applications since SPP modes are inherently lossy due to the resistive loss of the metal. There have been several SPP excitation schemes proposed in the literature. The most commonly used SPP excitation schemes are prism coupling in the Otto or Kretschmann configuration (Lukas Novotny, 2012) and metallic grating coupling [(Jiří Homola, 1999), (Anders Pors M. G.-C., 2014) (Tianran...
Liu, 2014). Tianran Liu et al. demonstrated a high efficiency dual layer grating SPP coupler for a gold/air interface (Tianran Liu, 2014). Pors et al. proposed and demonstrated 1D and 2D gap resonators for directional coupling of SPP modes (Anders Pors M. G.-C., 2014). Such couplers are highly efficient but require the out of plane bulky and angle sensitive coupling set up and perform well at narrow input beam cross sections. Therefore, such SPP coupling schemes are not suitable for compact, portable and integrated SPP excitation. For more compact coupling of SPP, scattering of light by transmission through a metallic nano-hole has also been demonstrated [ (Jing Yang, 2014), (Jiao Lin, 2013), (Wenjie Yao, 2015), (Dikken, Korterik, Segerink, Herek, & Prangsma, 2016)]. Jing yang et al. used an asymmetric optical slot nano-antenna pair to directionally excite SPP modes on a gold/air interface (Jing Yang, 2014). Lin et al. demonstrated polarization controlled tunable directional coupling of SPP modes using polarization sensitive apertures in a gold film (Jiao Lin, 2013). Yao et al. demonstrated directional SPP excitation using single element nano-grooves on a gold film (Wenjie Yao, 2015). In all these cases the nano-hole SPP excitation scheme have the drawback of low excitation efficiency. Furthermore, the SPP excitation efficiency is calculated by normalizing the power in the SPP mode by the incident power on the hole. The power incident on the geometric area of the hole is typically only a fraction of the total power carried by the incident beam. Therefore, SPP coupling efficiency numbers are even lower when the coupled SPP mode power is normalized to the total power in the beam. One possible solution to increasing the overall efficiency is to tightly focus the beam so that maximum power is incident on the aperture of the nano-hole. But, due to the diffraction limit, light cannot be focused tighter than approximately half of the wavelength. The SPP exciting nano-apertures typically have very small dimensions (smaller than the diffraction limit). Lalanne et al. have shown that the coupling efficiency of an SPP mode by scattering from a metal nano-hole gradually decreases with increasing width of the hole (P. Lalanne, 2006). Therefore, increasing the hole width to capture more power from the incident light does not improve the SPP coupling efficiency. Additionally, the SPP excitation efficiency further decreases with the increase in wavelength (P. Lalanne, 2006). Consequently, the SPP excitation efficiency in the telecom wavelength (1550 nm) is significantly lower than that in the visible region with the popular compact coupling techniques. To be compatible to the large variety of applications in the telecom wavelength regime, a compact and efficient method to excite SPP at the 1550 nm wavelength is very important. Mueller et al. have demonstrated fishbone structured plasmonic nano-antenna array for SPP coupling at 1550 nm; but
with a very low coupling efficiency (<1%) (Jing Yang, 2014). Li et al. demonstrated SPP coupling to a silver nano-wire at 1550 nm using a nano-tapered tip of fiber where the coupling efficiency is low and the setup demands extreme precision (Q. Li, 2011).

In their seminal paper, Reddick et al. demonstrated a near field photon tunneling scanning microscope (PSTM) capable of coupling evanescent light at an air-dielectric (glass) interface excited by total internal reflection (R. C. Reddick, 1989). In a similar fashion, an SPP mode can also be excited by total internal refraction using the Otto or Kretschmann configuration, as mentioned earlier. SPP modes excited by total internal refraction can also be imaged using PSTM by bringing the dielectric tip sufficiently close to the metal dielectric interface (J.-C. Weeber, 2001). In both Reddick and Weeber’s work, tunneling of photons through evanescently decaying field at the boundary of a metal dielectric interface has been utilized to couple to a propagating mode inside a dielectric tip structure placed in the near field. Metal coated dielectric tips have also been used to excite SPP at a metal/dielectric interface with relatively low excitation efficiency (~0.3%) (Bayarjargal N. Tugchin, 2015). The excitation efficiency of the SPP mode at the metal/dielectric interface at the near field of the tip depends on several parameters such as the shape of the tip, the distance of the tip from the interface and the refractive index of the tip as well as the medium surrounding the tip. In this chapter I investigate and carefully design a novel high-index dielectric gabled tip to directionally excite an SPP mode at a gold/glass interface at the telecom wavelength. Since our goal is to efficiently excite SPP in the 1550 nm wavelength Si is the convenient choice for the low loss high index material for the tip. I also experimentally demonstrate a high excitation efficiency of an SPP mode at a gold/glass interface using the designed Si gabled tip.

### 4.2 Proposed Design of the SPP Coupler

Figure 4.1 – a shows the schematic of the planned setup for the efficient excitation of an SPP mode. The base of the Si-tip collects the incident light from the beam with a larger cross-section and concentrates the energy supplied by the beam at the tip without leakage. The taper height can be adjusted to increase the base size to facilitate the capture of a larger beam cross section with a prior knowledge of the beam size. Hence, unlike most of the cases in the literature mentioned previously, the SPP excitation efficiency for the proposed technique can be calculated with respect to the total
energy supplied by the beam from the source rather than a partial cross section of the beam
determined by a nano-scale aperture.

Figure 4.1: a) Schematic of the SPP excitation setup by a Si-tip on a Si substrate. b) Simulated power profile of the
SPP excitation system in (a).

To achieve the a high SPP excitation efficiency I investigate the determining factors of near-field
coupling from a high index dielectric tip to a metal-dielectric interface. Since exciting an SPP
mode necessitates the generation of sufficiently matched momentum along the gold SiO$_2$ interface,
the refractive index and the and the shape of the tip play important role in exciting an SPP mode
at the interface. Additionally, the distance between the tip and the interface also affects the SPP
excitation efficiency. A commercial-grade 2D simulator based on the finite-difference time-
domain method was used to perform the calculations to carry out all the analyses regarding the
investigation of the various parameters of the SPP excitation setup discussed in this chapter
(Lumerical Solutions, Inc., n.d.).

4.3 Probing position for SPP Efficiency

Before delving into the discussion of such investigations it is necessary to establish the proper
definition of the SPP excitation efficiency considering the proper probing distance from the Si-tip
since the excited SPP mode exponentially decays as it propagates due to loss in the metal. The red
curve in Figure 4.2 plots the normalized power in the excited SPP mode (by the Si-tip) at 1550 nm
wavelength as a function of the probing distance ($d_{SPP}$ in Figure 4.1-a) from the tip. The black
dashed curve (Figure 4.2) shows the calculated exponential decay profile (normalized) of a
conventional single interface SPP mode at an Au/SiO$_2$ interface as a function of the propagation
distance. As can be observed from the two curves in Figure 4.2, the normalized power in the
excited SPP mode increases rapidly as $d_{SPP}$ increases from 0 to 4 $\mu$m and then exponentially decays
following the black dashed curve with further increase of the probing distance ($d_{SPP}$) than 4 $\mu$m.
This is an indication of the fact that light scattered from the Si-tip experiences near field interaction with the nearby metal/dielectric (Au/SiO₂) interface and gradually evolves into a coupled light-electron oscillation that starts propagating along the Au/SiO₂ interface. This evolution takes place in the region up to a 4 µm distance from the tip and from there the propagating mode attains the properties of an SPP mode. I consider this \( d_{\text{SPP}} = 4 \) µm to be the SPP excitation distance and calculate all the SPP excitation efficiencies at this distance from the Si-tip in our presented simulation results in the rest of the chapter.

![Figure 4.2: Simulated normalized SPP coupling efficiency as a function of probing distance from the Si-tip - \( d_{\text{SPP}} \) (red). For ease of comparison the calculated SPP decay profile is also presented (black dotted).](image)

### 4.4 Optimization of Tip Geometry

In the proposed SPP excitation scheme, the base of the Si-tip collects the incident light from the input beam and concentrates its energy at its tip, without leakage. The concentrated light from the tip then excites two propagating SPP modes, toward the right and left of the tip, at the Au/SiO₂ interface through near field coupling. At this point I consider the effect of sidewall angle (\( \theta \)) on the efficiency of the SPP excitation. Since the wavelength under consideration is 1550 nm and in that spectral region the convenient choice of low loss high index material is silicon, I choose Si as the material for the substrate and the gable shaped tip as shown in Figure 4.1 (a). Figure 4.3 plots the SPP excitation efficiency (in one direction i.e. the right side of the Si-tip in Figure 4.1-a) against the slope angle (\( \theta \)) of the Si taper tip. In Figure 4.3, there are two excitation peaks at 55° and 70° and the stronger peak is at 55°. This SPP excitation efficiency peak at 55° for the slope angle is a happy coincidence since the KOH wet etch of a <100> Si wafer etches at a slope angle of 54.7°, thus making the fabrication of the Si-tip optimized for SPP excitation quite inexpensive. From this
point in this chapter, for all the calculations, 54.7° is chosen as the slope angle of the Si-tip to obtain results relevant to the future experimental characterization of the fabricated device.

Figure 4.3: Simulated SPP excitation efficiency as a function of the slope angle of the Si taper tip.

To optimize the distance ($d$ in Figure 4.1(a)) between the tip and the Au/SiO$_2$ interface, I consider two cases of the tip geometry – a sharp tip and then a 500-nm wide tip. Ideally, a sharp tip would be the best choice for the SPP excitation scheme. But for KOH etching one should create a mask of a finite width (i.e. a SiO$_2$ mask) resulting in a finite width of the Si-tip. To be consistent with the dimensions of the fabricated tip presented later in this chapter a flat tip (500 nm width) is considered and its SPP coupling efficiency is compared to that of a sharp tip. Figure 4.4 shows the change in SPP excitation efficiency with the change in the distance ($d$ in Figure 4.1-a) between the Si-tip and the metal dielectric (gold/glass) interface. For a sharp Si-tip the SPP excitation is maximum at $d = 0$, i.e. the Si-tip is touching the gold. The efficiency gradually decays as $d$ increases. For a 500 nm flat tip the maximum SPP coupling efficiency is achieved at $d = 100$ nm and it gradually decreases as $d$ is further increased. In an addition, the peak excitation efficiency for a flattened tip (500 nm wide) is lower than that for the case of a sharp tip due to reduced field intensity at the tip region and increased reflection at the flat surface.
From the above findings, I chose the parameters for the optimum geometry of the presented SPP excitation scheme to be a $54.7^\circ$ sidewall angle ($\theta$) of the Si-tip and a 100-nm distance ($d$) from the flat tip to the Au/SiO$_2$ interface. These values will be used throughout the rest of the chapter (unless specified). With the optimum geometry of a sharp tip as discussed above, 29% (58% considering excitation on both sides) of the power at 1550 nm wavelength of the incident broad beam at the base of the Si-tip (10.4 $\mu$m beam diameter) is converted to the characteristic SPP mode of the Au/SiO$_2$ interface on one side of the Si-tip at the 1550 nm wavelength. For a 500 nm, flat tip, the single sided coupling efficiency drops down to $\sim$23.56% at 1550 nm as mentioned earlier ($\sim$ 47% on both sides). Despite the absence of a sharp tip, such high SPP excitation efficiency demonstrates the robustness of this scheme to fabrication imperfections.

### 4.5 Unidirectional SPP excitation

Until this point I have discussed the SPP excitation scheme with a bi-directional excitation as such the excitation of the SPP occurs in a symmetric fashion towards both sides of the gable shaped Si-tip structure. However, for some applications it is important to be able to excite a unidirectional SPP mode with control over the excitation direction. Using the same setup as shown in Figure 4.1-a, it is possible to excite a unidirectional SPP by only laterally displacing the position of the incoming beam. A displacement towards the right excites an SPP on the left-hand side of the tip and vice versa. The directional excitation of SPP by source displacement is depicted in Figure 4.5-(a) and (b). For a 10.4 $\mu$m beam diameter, the calculated directional SPP excitation efficiency can reach up to 31% at the 1550 nm wavelength. To reduce the leakage of power due to the tail of
the Gaussian beam being pushed out of the base of the Si-tip, one can reduce the beam diameter or increase the base size of the tip keeping the sidewall angle unchanged at 54.7°. The calculated directional excitation efficiency for the 5 μm MFD input beam is ~52% at 1550 nm wavelength for a flat Si-tip. Figure 4.6 shows the extinction ratio of the power of the SPP excited to the left of the tip to that of the right side which is larger than 14 dB for the broad wavelength window of 1500 to 1600 nm.

![Figure 4.5: a) Simulated power profile for unidirectional SPP excitation on a) the left side by displacing the source to the right, b) the right side by displacing the source to the left. The source was displaced by 1.89 μm to the left.](image)

![Figure 4.6: Simulated extinction ratio of the power of the SPP excited on the left to that on the right for a source displacement to the right.](image)

### 4.6 Sample Plan for Characterization

With all the optimized parameters at hand the next step was the fabrication and the characterization of the fabricated sample. Since there is no direct access to the excited SPP mode as it is excited at
the bottom Au/SiO$_2$ surface (as depicted in Figure 4.1-b and Figure 4.5), gratings were added in the gold (Au) layer in the sample layout in order to couple the excited SPP into a radiating mode at a certain angle which later can be picked up and measured at the detector in the characterization setup. A full 3D schematic depiction of the gabled tip SPP excitation device along with couple-out grating can be found in Figure 4.9-a. The grating parameters were designed from the effective index of the excited SPP mode at the bottom Au/SiO$_2$ interface so that the SPP mode converts to a radiating mode at a direction 23$^\circ$ off from the normal direction as depicted in Figure 4.9-a. The calculated effective index of the SPP mode for the Au/SiO$_2$ interface is 1.4562. The period of the designed grating was 840 nm with a 60% duty cycle. The phase matching equation below was used to design the grating period for the SPP radiation at 23$^\circ$.

$$-k_{\text{air}}\sin\theta = k_{\text{SPP}} + \frac{2m\pi}{\Lambda}, \quad m = 0, \pm1, \pm2, \pm3 \ldots \quad (4.1)$$

The Duty cycle was optimized for maximum power conversion to the radiated mode using particle swarm algorithm in Lumerical FDTD (Lumerical Solutions, Inc., n.d.). Figure 4.7 shows the schematic of the setup considered to calculate the phase matched grating parameters for a radiation angle of $\theta = 23^\circ$.

![Figure 4.7: A typical diffraction grating structure (like the one fabricated on the chip) showing the parameters to consider for phase-matching calculations.](image)

The specific angle of radiation was chosen to verify that the excited mode at the Au/SiO$_2$ interface is indeed an SPP mode. A radiated beam from the designed grating at an angle $\theta (23^\circ)$ as shown in Figure 4.7 can only result from a phased matched conversion from an SPP mode at the Au/SiO$_2$ interface. Therefore, in the experimental measurements it is expected to find a radiation from the designed grating directed towards the 23$^\circ$ off-normal direction. Additionally, to investigate the lossy propagation of the SPP mode several gratings were designed to be fabricated at different
distances from the tip of the Si gabled tip structure. The power decay rate in the radiated beam from the gratings at different distances from the gable shaped tip would reflect the loss characteristics of the excited SPP mode. Furthermore, a visualization gap (Vis. Gap in Figure 4.8) was created during the E-beam lithographic process of the metal layer for imaging different planes along the beam path through the sample substrate. Such imaging was achieved by adjusting the focus of the input objective lens along the input beam path in the measurement setup. Figure 4.8 depicts the top view of the sample floor plan before fabrication.

![Figure 4.8: Top view of the floor layout plane for the sample fabrication](image)

### 4.7 Fabrication

To experimentally realize the Si-tip SPP coupling, as mentioned previously, I used the KOH wet etch process of <100> Si to obtain a preferential etch slope of 54.7° of the Si-tip. To avoid an omnidirectional excitation of SPP, instead of a cone shaped Si-tip, I chose to fabricate a gable shaped tip structure of Si as depicted in the schematic diagram of the device in Figure 4.9 - a. Figure 4.10 shows the steps for fabricating the gabled Si-tip SPP excitation device. To fabricate the device, I first obtained a piece of <100> Si wafer and grew 300 nm of SiO₂ by thermal oxidation.
(18 mins in the Bruce Technologies Oxidation Furnace at TNFC). Then patterns of 500 nm wide and 5 mm long lines as well as 200 micron square pads were made on a ma-N 2405 negative resist layer on top of the oxidized Si sample using Vistec E-beam lithography unit at the TNFC fabrication facilities of the University of Toronto. Next, oxide etch was carried out by the Oxford Instruments PlasmaPro Estrelas100 DRIE System (Si) at the TNFC fabrication facilities. This left the <100> Si wafer surface masked by 500 nm thin lines of SiO₂ for the KOH wet etch. The wet etch of Si masked by SiO₂ lines was carried out by submerging the patterned sample in 45% KOH solution for 10 mins at 80°C temperature. As KOH etch of Si is faster in the <100> direction as compared to the <111> direction, the etch creates a sidewall slanted by 54.7° from the edge of the mask line as shown in Figure 4.10. Therefore, as the wet etch progressed, the slanted sidewalls on both sides of the 500-nm wide SiO₂ mask lines created a gabled tip shaped Si taper structure with a 500-nm wide tip and 6 µm height. Then a thick (more than 6 µm) PECVD oxide was deposited on top of the fabricated Si chimneys using Oxford Instruments PlasmaLab System 100 PECVD. Then I planarized the top surface of the deposited PECVD oxide using chemical mechanical polishing (CMP). The bottom surface of the sample (rough Si) was also polished for reducing the defused reflection while coupling light from the bottom. The oxide on the top surface was polished until the oxide surface reached the same level as the tip of the Si gabled tip structure. Then negative resist (ma-N 2405) was patterned on the oxide surface for metal deposition and grating fabrication using the same electron beam lithographic system at TNFC. The 200 µm square Si marker pads were used for alignment of the resist patterns for proper positioning of the grating. Then gold was deposited on top of the patterned resist using a Datacomp Electronics TES12D Thermal Evaporator. Lift-off of the metal layer was carried out by dipping the sample into Acetone and undulating the beaker to fabricate the grating designed to out-couple the excited SPP mode at the Au/SiO₂ interface at a -23° angle from the normal. In the fabricated sample the grating was 10 µm away from the tip of the Si chimney. Hence the excited SPP mode can propagate for 10 µm before getting coupled out from the grating at the set -23° angle.
Figure 4.9: a) Schematic diagram of the fabricated sample for the Si gabled tip SPP coupling setup with the out-coupling grating in the metal tuned to the SPP mode index. The two gratings in the schematics start at two different distances $d_1$ and $d_2$ from the position of the Si-tip. In the fabricated sample, I have six different gratings starting at gradually increasing distances. Only two of them are shown in the schematic. b) A Scanning Electron Micrograph of a gabled Si-tip covered with SiO$_2$ and gold layer and grating on top in one of the fabricated samples. As can be seen from the SEM the tip to metal distance is large in this sample. This low performance sample was used as a sacrificial sample for SEM imaging.

Figure 4.10: Steps of fabricating the on-chip Si gabled tip SPP excitation device.
4.8 Characterization

I used two different measurement setups for efficiency measurement of the SPP excitation and the radiation pattern measurement from the grating as mentioned in the last section. For efficiency measurement, I used the setup as shown in Figure 4.11-a. Light was collected from a JDS Uniphase SWS15101 Tunable Laser Source tuned to the 1550 nm center wavelength, using a single mode fiber (SMF); then converted to a free space Gaussian beam using a fiber collimator lens. The beam propagates through a polarization control optics section in the setup and coupled to the base of the gabled Si-tip using Newport F-L40B objective lens. At the output, light was collected using a Newport M40X objective lens and focused onto the Newport 818-IR detector.

Figure 4.11: a) A Schematic of the experimental setup for imaging the radiated surface plasmon from the metallic grating. b) A schematic of the experimental setup for measuring the radiation pattern of the metallic grating with a movable detector.
For the radiation pattern detection, the measurement setup is depicted in Figure 4.11-b in which the beam traverses through the similar components as shown in Figure 4.11-a, and delivered to the base of the gable shaped Si-tip. The sample was attached to the fixed center stage of the custom-built radiation pattern measurement setup where the Newport IR (Infrared) detector was attached to the rotational stage which rotates in the horizontal plane around the sample to collect scattered light and measure the radiation pattern of the sample on the center stage (Figure 4.11-b). For each of the measurement cases shown in Figure 4.11, during the power measurement, the input beam was focused such that the beam waist lies at the base of the Si gable shaped tip. Such focusing was achieved by moving the input objective lens along the beam path, closer or further from the vertically held sample on the stage. A sharp image of the features in the sample lying in the focal plane of the beam was created in the imaging camera. By observing the sharp features in the image plane (camera) the focus was adjusted to lie in the plane of the base of the gable tip. The output objective lens (Figure 4.11-a) was aligned to the Vis. Gap (Figure 4.8) while such focusing was performed. Then the sample position along the beam path (distance from the input objective lens) was locked and it was moved along the transverse plane to achieve maximum radiation from the gratings. At that point, the power measurements were performed – the results of which are presented in the following section.

4.8.1 Measurement Results

In the experiment for characterizing the fabricated sample, light is launched into the gabled Si-tip from the bottom as depicted in Figure 4.9-a by focusing the beam at the base of the gabled Si-tip using an objective lens with large working distance. Therefore, the light concentrated at the tip by the Si-tip is coupled to the SPP mode either in a unidirectional, or a bidirectional manner (as discussed earlier) depending on the position of the input beam. In the experiment, I positioned the beam to obtain maximum output from the grating. In other words, the center of the input beam was displaced from the center of the base to have more power to be directed to the SPP excited to the side of the gabled Si-tip where the grating was fabricated. Therefore, the excited SPP was a directional SPP as depicted in Figure 4.5. The radiated beam from the grating was collected using the output objective lens with a large numerical aperture. Figure 4.12 shows the camera images of the excited SPP out-coupled to a radiation mode from the gratings at the three different distances from the Si-tip. The decay in the power of the radiated mode indicates the plasmonic nature of the
mode that is being radiated by the grating. Additionally, switching the input polarization from $p$ polarized to $s$ polarized light, the output from the grating vanishes (as shown in figure 4(d)). SPP modes are characteristically $p$ polarized in nature. Therefore, the vanishing of the output from the grating for $s$ polarized input is a further indication of the plasmonic nature of the mode excited by the Si gable shaped Si-tip.

Figure 4.12: Camera image of the gabled Si-tip excited SPP mode radiated from the grating at a) 10 $\mu$m, b) 30 $\mu$m and c) 40 $\mu$m away from the tip for $p$ polarized illumination of the Si-tip base. d) Camera image of the grating at 10 $\mu$m away as in case – a with an $s$ polarized illumination. Switching the polarization makes the radiation from the grating to go dark.

To further establish the fact that the detected light is indeed an SPP mode excited by the Si-tip, which is out-coupled through the grating, I have measured and calculated the angular intensity pattern of the radiated light from the sample. As stated earlier, the grating was designed such that enforcing the phase-match condition between the excited SPP and grating will produce a radiating beam at $-23^0$ with respect to the normal (see Figure 4.9-a). Figure 4.13 shows the calculated and measured radiation patterns from the grating ($d_1 = 10 \mu$m) when the base of the Si-tip is illuminated from the bottom. In figure 5, the green dashed line is the measured radiation pattern and the black dotted line is the simulated radiation pattern when the SPP is excited via the Si-tip and out-coupled by the grating. The red solid curve is the radiation pattern when the grating is excited by a conventional single interface SPP mode. The agreement among all the curves in Figure 4.13 clearly indicates that the mode excited by the Si gable tip at the Au/SiO$_2$ interface is indeed an SPP.
Having established that the excited mode at the Au/SiO$_2$ interface was indeed an SPP mode, the focus was directed towards measurement of the excitation efficiency. From the detector readings of the characterization setup as shown in Figure 4.11-a it was measured that $8.89\%$ of the input power at the base of the gabled Si-tip is power radiated from the grating. However, this number does not represent the achieved SPP coupling efficiency and requires further extrapolation considering a few factors such as a) the beam width with respect to the base size of the gabled tip, b) the grating conversion efficiency, c) the roughness of the Au/SiO$_2$ interface and, d) the distance between the tip and Au layer. By an SEM microscopy of the sample, I measured the fabricated tip dimension and the tip-metal distance achieved by polishing. The tip height in the fabricated sample was 6 $\mu$m which translates to a base length of 8.5 $\mu$m (since the slope angle of the Gabled tip sides are $54.7^\circ$ determined by the KOH Si etch) while diameter of the incident beam from the input objective lens was 10 $\mu$m. Hence, the displaced positioning of the beam from the center of the base to achieve a unidirectional excitation resulted in a considerable portion of the tail of the Gaussian beam missing the base of the Si-tip structure. Therefore, power carried by the missing portion of the tail of the Gaussian beam did not enter the gabled Si-tip and eventually did not couple to the SPP mode. The other major factor under consideration is the power transfer efficiency of the fabricated grating structure. Additionally, the first grating was fabricated 10 $\mu$m away from the vertex of the Si-tip. In our previous discussions, I established the SPP excitation distance to be 4 $\mu$m ($d_{\text{SPP}} = 4 \, \mu\text{m}$). Therefore, the SPP excited by the Si-tip propagated for 6 $\mu$m before reaching...
the grating structure and there is a loss associated to the propagation of the SPP mode due to the absorption in metal.

![Diagram](image)

**Figure 4.14:** (a) Schematic of the end view of the Si-tip SPP excitation scheme. (b) Normalized power decay of the SPP mode excited by the Gabled Si-tip. The red solid curve plots the decay profile of the Au/SiO$_2$ single interface SPP mode excited by the Si-tip, the diamond shaped data points are measured normalized power radiated from the gratings at different distances and the greed dashed curve is the exponential fit to the measured data points.

Furthermore, In the simulations I have considered a smooth Au/SiO$_2$ interface while in the fabricated sample, the interface was imperfect and had an average roughness ~ 20 nm. All these factors, in an addition to SPP excitation, contribute to the loss of optical power before the radiated beam from the grating reaches the detector.

To estimate the actual propagation loss of the SPP in the sample, as mentioned earlier, several gratings were fabricated at varying distances from the vertex of the tip. The power radiated from the gratings fabricated at different distance (6 µm, 66 µm and 96 µm) from the SPP excitation point of $d_{SPP} = 4$ µm (see Figure 4.8) was recorded to estimate the propagation loss in the fabricated sample. At last but not the least, the tip - Au layer distance ($d$) in the fabricated sample was measured to be 271 nm. Below is a description of the technique adopted to estimate the actual SPP excitation efficiency by an extrapolation from the 8.89% power captured by the detector, considering all the different loss contributions mentioned above.

### 4.8.2 Extrapolation of SPP Excitation Efficiency

Because of fabrication imperfections (i.e. roughness at the Au/SiO$_2$ interface, random scattering centers, lower grating conversion efficiencies in reality) the attenuation of the propagating SPP mode in the device is larger than the attenuation of the SPP mode at the calculated smooth Au/SiO$_2$ interface. As mentioned previously, 8.89% ($\eta_{out}$) of the light from the input beam is radiated out from the grating at the preferential angle designed to out-couple the SPP. A quick simulation plugging the fabricated grating parameters obtained by scanning electron microscopy, gives us a
41.89% grating conversion efficiency ($\eta_{\text{grating}}$ as shown in Figure 4.14(a)). The Red solid curve in Figure 4.14(b) plots the calculated decay profile of the normalized power in the SPP mode excited by a gabled Si-tip. The black diamond shaped data points are the measured normalized power radiated from the gratings at different distances from the tip position as shown in Figure 4.9(a). The green dashed curve in Figure 4.14(b) is an exponential fit to the black diamond shaped data points obtained from measurement. The parameter $\alpha$ (Figure 4.14(a)) accounts for the attenuation (due to propagation) of the SPP mode excited by the Si-tip (see Figure 4.14(a)). The calculated value of $\alpha$ associated to the red solid curve in Figure 4.14(b) is $0.0127/\mu$m ($\alpha_{\text{calc}}$). The value of $\alpha$ associated to the green dashed curve (exponentially fitted to the data points of measurement) is $0.0312/\mu$m ($\alpha_{\text{exp-fit}}$). Such significant difference in magnitudes of $\alpha_{\text{calc}}$ and $\alpha_{\text{exp-fit}}$ is a clear indication of the fact that the imperfect fabrication resulted in a higher attenuation (due to propagation) of the excited SPP in the fabricated sample. The extrapolation of the actual SPP coupling efficiency ($\eta_{\text{SPP-tip}}$) is done using the following equation:

$$\eta_{\text{SPP-tip}} = \frac{\eta_{\text{out}}}{\eta_{\text{grating}}} \times e^{\alpha_{\text{exp-fit}} L}$$  

(4.2)

The obtained efficiency ($\eta_{\text{SPP-tip}}$) for a propagation distance of $L = 6 \mu$m in equation 4.2 was 25.52%. As mentioned above, the differences in the values of $\alpha_{\text{calc}}$ and $\alpha_{\text{exp-fit}}$ comes from the fact that $\alpha_{\text{calc}}$ was calculated considering a perfectly smooth Au/SiO$_2$ interface and a perfect homogeneous SiO$_2$ layer underneath the Au layer. The Au/SiO$_2$ interface in the fabricated sample was not perfectly smooth; also, random scattering centers could exist in the SiO$_2$ layer near the interface. Hence, as expected, $\alpha_{\text{exp-fit}}$ was found to be larger than the $\alpha_{\text{calc}}$. Therefore, the measured SPP excitation efficiency is 25.52% while, plugging the geometric parameters (i.e. the grating parameters and the tip Au distance of 271 nm) of the fabricated sample and the large 10 \mu m MFD of the input beam, the simulated SPP excitation efficiency was 26%. Thus, to conclude, a very good agreement between the predicted and the measured SPP excitation efficiency was achieved in the characterization of the fabricated sample.

4.9 Applications

As discussed in the Introduction section of this chapter, SPP can find their application in numerous fields of photonics. Each of those applications require a highly efficient and directional SPP excitation technique. The commonly present SPP excitation techniques are rather bulky and if not,
inefficient. The demonstrated Gable shaped Si-tip SPP excitation scheme can be very useful in two utilitarian aspects: efficiency and compactness. Hence, this demonstrated excitation scheme can find its application in making compact SPP sensors where the problem lies in miniaturization of the SPP excitation setup (the prism or grating coupling either needs bulky setups). This on-chip mechanism helps get rid of the voluminous setup of SPP excitation while keeping the SPP excitation efficiency high. Furthermore, the proposed SPP excitation mechanism is comparable to, if not surpasses by orders of magnitude, the excitation efficiency to the other SPP excitation techniques out in the literature with similar compactness.

Additionally, effectiveness in the telecom wavelength (1550 nm) makes the proposed SPP excitation scheme more viable for the purpose. This proposed scheme can be deemed very useful as optical via for vertical integration of a multilayer plasmonics-electronics hybrid platform. As shown by the power profile plot in Figure 4.15-a, besides exciting SPP, the Si gabled tip can capture a propagating SPP in the same fashion it can excite and SPP. In the telecom wavelength, the SPP probing efficiency can go as high as ~ 86%. Figure 4.15-b shows the simulation results (power flow plot) of the proof of concept simulation of a complete SPP excitation and probing system compatible to vertical integration. As indicated by the yellow arrow it is evident that a vertical beam (can be emitted from a VCSEL) is coupled to a horizontally propagating SPP mode and is then captured by the gabled Si-tip SPP probe that works as via to pull the light to the bottom layer. With some further modifications and noise reduction, this technique can be very useful for integration of electronics and photonic platforms in a multilayer stacked electro-optic chip.
At last but not the least this high efficiency SPP excitation scheme can find numerous applications in achieving nonlinear SPP interaction of light with metal or nonlinear polymers (as the dielectric instead of SiO$_2$) by further concentrating the excited SPP by an adiabatic taper in the metal layer.

4.10 Conclusion

To summarize, I have proposed and demonstrated a new and very compact technique to efficiently excite an SPP mode at a metal dielectric interface using a high index (Si) gabled tip structure at the 1550 nm wavelength. In our analysis, a perfectly fabricated sharp tip with the optimized parameters would excite a bidirectional SPP with 29% efficiency (on each side of the tip) with respect to the power carried by a broad beam of 10.4 μm. For a flattened tip the excitation efficiency can reach a 23.56% (on each side) which is orders of magnitude higher compared to the other compact SPP excitations schemes in literature. A slight displacement of the source from the center of the base excites the SPP in a unidirectional fashion with an efficiency ~ 52% which is higher than any theoretically achievable SPP excitation efficiency reported in literature to our knowledge. I developed a fabrication process for the device and demonstrated a ~25.5% coupling efficiency of a unidirectional SPP mode using the fabricated device. The efficiency can be further improved narrowing down the tip dimension and further, smoothening the metal dielectric interface. The proposed scheme is a very compact, on-chip SPP coupling technique. Using the proposed technique, a substantially high and directional SPP excitation efficiency is achievable without the need of an out of the plane angular excitation setup. The excitation efficiency is measured with respect to the power carried by the incident beam instead of a portion of the incident power on the device geometry. The excitation scheme can also accommodate a large input beam size. For the purpose, one should carry out the wet etch of Si for a longer time to create a larger base size of the gable shaped tip structure. The coupling efficiency achieved by using the demonstrated scheme is orders of magnitude higher than other proposed setups of comparable compactness.
Chapter 5. A Reduced Noise Excitation of Surface Plasmon Polariton

In the previous chapter I presented the design, fabrication and characterization of a highly efficient and ultra-compact surface plasmon polariton (SPP) excitation scheme using a gable shaped silicon (Si) tip. While the scheme is quite useful in applications requiring an efficient excitation of SPP in photonic circuits, it requires further modifications for applications such as sensing because the excited SPP is not accessible from the air-side (above the metal’s surface). The major reason is that the SPP mode was excited at the bottom Au/SiO₂ interface. In this chapter I take my initial investigation further to engineer a Si gabled tip which can excite the SPP mode at the top interface between the Au film and air. I present the detailed optimized design of the SPP excitation mechanism with a reduced noise and more accessibility to the excited SPP mode.

5.1 Introduction

As discussed in Chapter 4 a properly engineered Si gable shaped tip structure is capable of efficiently exciting an SPP mode at a metal dielectric structure by near field coupling. It was demonstrated that 52% directional SPP coupling efficiency is achievable using the setup. As mentioned at the end of Chapter 4, this SPP excitation scheme can be very useful in miniaturization of SPP based sensors. There have been reports of development of miniaturized optical on-chip sensors in the literature. Bahrami et al. proposed and demonstrated an efficient hybrid SPP based sensor with prism coupling of the SPP mode (Bahrami, Maisonneuve, Meunier, Aitchison, & Mojahedi, 2013). Swiontek et al. also used the same prism coupling setup to excite SPP mode for their sensors (Swiontek, Pulsifer, & Lakhtakia, 2013). There are such several other examples of SPP sensors in literature using either localized surface plasmon resonance (LSPR) or propagating SPP modes for sensing purpose. However, despite the advantages like enhanced degrees of freedom for sensing with an excited SPP mode, researchers tend to rely on localized surface plasmon resonance since the excitation of SPP mode is rather critical and a large angle dependent setup is required (Li, Cushing, & Wu, 2015). Regarding this problem of exciting an SPP mode in a compact setup, the gable shaped tip SPP excitation scheme as presented in Chapter 4, can be very effective for the miniaturization of SPP sensors. However, for such applications the major
drawback of the setup is reduced accessibility of the excited SPP mode. One should engineer a buried microfluidic channel underneath the metal layer to have the SPP mode to be in direct contact with the fluid under investigation. In this chapter, I introduce a few modifications to the geometry presented in Figure 4.9-a in Chapter 4. In the modified geometry, the Si-tip penetrates the metal layer through an aperture and is covered by a SiO$_2$ cap. Figure 5.5-a shows the end view of the modified SPP excitation geometry. The modified gable Si-tip structure successfully demonstrates the excitation of an SPP mode at the top Au/air interface with high excitation efficiency. In a similar fashion as presented in Chapter 4, the excitement efficiency is calculated with respect to the total power in the beam incident on the demonstrated structure and the design is flexible to the size of the beam waist.

5.2 Design of the Gabled Tip SPP Coupling Scheme for Top Excitation

Despite the modifications made to the geometry presented in Chapter 4, the design basis of the excitation scheme is still the silicon (Si) gabled tip structure as in the previous chapter. Since the fabrication involves KOH etch of <100> Si wafer, during the design analysis in Lumerical FDTD (Lumerical Solutions, Inc., n.d.), 54.7$^\circ$ slope of the gable shaped tip and a 500-nm width at the tip was used for the device geometry. To make the tip visible to the tip Au/air interface, the design was modified in such a way where, the tip penetrates the metal layer through an aperture and a portion of the tip emerges into the air as shown in Figure 5.1(a)

![Figure 5.1: a) Schematic diagram of an SPP excitation setup to the top Au/air interface. b) Achieved SPP excitation efficiency (%) with the setup depicted in part-a.](image)

Figure 5.1-b shows the SPP excitation efficiency spectrum to one side of the gable shaped tip structure for a bidirectional excitation using the scheme depicted in Figure 5.1-a. As evident in Figure 5.1-b, the excitation efficiency is quite low when compared to the efficiency presented in
the previous chapter. At this point I investigate the cause of such low SPP excitation efficiency which leads to the following detailed analysis of the excitation mechanism of the SPP at the Au/air interface.

### 5.2.1 SPP Excitation Mechanism at the Top Au/Air Interface

Per Fresnel’s law of reflection, when light is incident at the interface between two medium of different refractive indices, part of it gets reflected and the rest gets transmitted (considering loss less transmission) from the first medium to the second medium (depiction in Figure 5.2-a). Considering the case as shown in Figure 5.2-b where a freely propagating beam inside a medium i.e. SiO₂ is incident at the meeting point of three different interfaces – an air/SiO₂ interface, a metal/air (Au/air) interface and an Au/SiO₂ interface as shown in Figure 5.2-b. In accordance to the depicted setup in Figure 5.2-b, the propagating beam will experience a change in refractive index from $n_{\text{oxide}}$ to $n_{\text{eff-SPP}}$. Here, $n_{\text{oxide}}$ is the refractive index of SiO₂ and $n_{\text{eff-SPP}}$ is the effective index of the fundamental SPP mode under consideration that exists at the Au/air interface. Therefore, a portion of the energy in the incident beam from SiO₂ will be transmitted to the SPP mode with an effective index of $n_{\text{eff-SPP}}$ as shown by power density profile in Figure 5.2-c. The rest of the incident energy will either be reflected into the SiO₂ or converted to a scattered radiation into the air as can be seen in Figure 5.2-b & c.

![Figure 5.2](image)

*Figure 5.2: a) Schematic of reflection at an interface between two medium of refractive indices $n_1$ and $n_2$. b) Schematic of propagating light in glass being converted to an SPP mode of effective index $n_{\text{eff-SPP}}$ upon incidence at the meeting point of the glass, air and gold (Au) slabs. c) Simulated power flow profile indicating light converted to an SPP mode.*

The efficiency at which the incident power gets converted to an SPP mode as depicted in Figure 5.2-c is dependent on a few factors i.e. the position of the beam center relative to the Au/air interface ($h$ in Figure 5.3-a), the angle of incidence of the beam ($\theta$ in Figure 5.3-b), as well as the mode field diameter (MFD) of the beam. The effect of the vertical position ($h$) of the input beam and the angle of incidence ($\theta$) on the SPP excitation efficiency is shown in Figure 5.3-c & d.
Figure 5.3 shows that for normal incidence \( (\theta = 0^0) \) the maximum coupling to an SPP mode occurs for a vertical displacement \( h \) of 276 nm of the beam of 5 \( \mu \)m MFD. On the other hand, setting \( h \) to be 276 nm, the SPP coupling efficiency was found to be maximum for an angle of incidence \( \theta \) of 2.5\(^0\) (Figure 5.3-d). Intuitively, one might expect the maximum SPP coupling to occur at the normal incidence of the beam \( (\theta = 0^0) \). However, due to the non-zero breadth of the beam (i.e. 5 \( \mu \)m MFD) a slightly inclined beam pointing towards the edge of the Au/air/gold interface meet up point results in a maximum amount of the beam cross section being visible by the Au/air interface to be coupled to an SPP mode. At normal incidence (i.e. \( \theta = 0^0 \)), the optimum vertical displacement \( h \) for maximum coupling to the SPP mode was 276 nm for a Gaussian beam with beam radius of 2.5 \( \mu \)m. Therefore, almost half of the beam cross section would be unavailable to the Au/air interface unless the beam is slightly inclined at an angle \( \theta \) as shown in Figure 5.3-b. Hence, a slightly angled incidence (i.e. \( \theta = 2.5^0 \)) facilitates a better coupling to SPP for the setup depicted in Figure 5.3-a.
Now, returning to the problem of excitation of SPP at the Au/air interface using the Si-tip, a further detailed treatment of the beam path inside the Si-tip structure (like Figure 3.1) is required to understand the coupling process. For the case of a Si-tip submerged in air, the angle of release for the beam ($\theta_{rl-air}$) was calculated to be $\sim 35^0$ in Chapter 3 (Figure 3.1). Changing the surrounding medium from air to SiO$_2$ as depicted in Figure 5.4 results in the angle of release ($\theta_{rl-oxide}$) to be changed to $5.5^0$ which is close to the optimum angle of $2.5^0$ (Figure 5.3-b) as opposed to $\theta_{rl-air} = 35^0$ for an air surrounding. Therefore, instead of air, if the Si-tip is submerged completely in SiO$_2$ then the resultant $\theta_{rl-oxide}$ will facilitate a more efficient excitation of an SPP mode at a nearby Au/air interface. Hence, as a solution to the problem of low SPP excitation efficiency as can be found in Figure 5.1-b, the excitation geometry was modified and a cap structure of silicon di-oxide (SiO$_2$) was added on the protruding portion of the gabled Si-tip structure. Figure 5.5 shows the capped SPP excitation device structure (part-a), the power density profile (part-b) and the spectrum (part-c) of the excitation efficiency to the SPP mode of the Au/air interface using the revised (capped) structure. The Au/air interface bidirectional SPP excitation efficiency has increased from a mere $2.5\%$ (in Figure 5.1-b) to almost $\sim 15\%$ (considering one direction) in Figure 5.5-c due to the incorporation of the SiO$_2$ cap at the tip.
Having, modified the Si-tip geometry for SPP excitation at the top (Au/air) interface, in the similar fashion as Chapter 4, I investigated the ideal probing position to define the SPP excitation efficiency. The analysis was done by probing the SPP power at different distances ($d_{SPP}$) from the edge wall of the SiO$_2$ cap as shown in Figure 5.5-a. In a 2D simulation domain in the Lumerical FDTD (Lumerical Solutions, Inc., n.d.), I varied the probing distance ($d_{SPP}$) and recorded the normalized SPP power at 1550 nm wavelength for each probing point. The red solid curve in Figure 5.6 plots the transverse power profile of the excited SPP mode (along the y–y’ line at different positions i.e. different values of $d_{SPP}$ in Figure 5.5-a) and compares it to the characteristic SPP mode profile at an Au/air interface. The evident similarity of the two excited mode profiles demonstrates the SPP nature or the excited mode. Figure 5.7 plots the normalized power of the excited SPP mode using the oxide capped Si gabled tip structure with $d_{SPP}$ varying from 0 to 78 µm and compares it with the characteristic propagation decay of the SPP mode at an Au/air interface. As evident in the red curve in Figure 5.7, one can observe that the SPP power is the maximum when $d_{SPP} = 0$, meaning, right at the start of the metal film adjacent to the SiO$_2$ cap sidewall. The black solid curve presents the normalized SPP exponential decay due to the lossy propagation characteristics of the SPP mode along the Au/air interface. From the edge of the oxide cap, as the excited SPP mode propagates, it follows the similar propagation decay as that of the characteristic SPP mode of the Au/air profile with some deviation. Therefore, for the oxide capped gabled tip SPP excitation scheme, $d_{SPP} = 0$ is the probing distance at which SPP excitation efficiency is defined.
Figure 5.6: Excited SPP profile using the oxide capped gabled tips scheme along the $y-y'$ line at the Au/air interface (red curve) as compared to the characteristic SPP power profile along the $y-y'$ line at the Au/air interface as shown in Figure 5.5-a. The position of the $y-y'$ line has been changed for different values of $d_{SPP}$ in order to view the SPP profile at different distances along the interface. Figure was obtained using Lumerical FDTD simulations.

Figure 5.7: Simulated normalized power of the propagating SPP mode excited by the gabled Si-tip as a function of $d_{SPP}$. The red curve plots the normalized power profile. (Please see Figure 5.5-a for the device geometry).

5.2.2 Optimization of the Oxide Capped Tip Structure

Since the proper definition of the SPP coupling efficiency has been established focus is directed towards the optimization of the proposed structure for enhancing the coupling efficiency even further. Since the purpose of the device of is to excite an SPP mode at the top Au/air interface, it is important to figure out how much of the protruding tip through the metal aperture should be visible to the Au/air interface. Such visibility is quantified by the two parameters $h_{Tip}$ and $w_{Cap}$ as shown in Figure 5.5-a. The parameter $h_{Tip}$ denotes the height of the portion of the gable shaped tip.
protruding out of the metal gap and $w_{\text{Cap}}$ denotes the width of the oxide cap that covers the protruding tip of the Si.

Figure 5.8: a) Simulated normalized SPP power as a function of the protruding tip height ($h_{\text{Tip}}$) from the metal gap. b) Simulated normalized SPP power as a function of the oxide cap width ($w_{\text{Cap}}$). For the definitions of $h_{\text{Tip}}$ and $w_{\text{Cap}}$ see Figure 5.5-a.

Figure 5.8 plots the normalized SPP power at the oxide cap wall edge as a function of $h_{\text{Tip}}$ and $w_{\text{Cap}}$. As evident from the figure, the optimized values for $h_{\text{Tip}}$ and $w_{\text{Cap}}$ are found to be 2.7 $\mu$m and 4.6 $\mu$m respectively. With the optimized geometry for the oxide capped SPP excitation scheme one can achieve $\sim$ 15.5% of SPP mode excitation efficiency in one side of the gabled tip for a bidirectional excitation scheme (total $\sim$ 31% of light excited into SPP) as depicted by the SPP excitation efficiency spectrum in Figure 5.9.

Figure 5.9: Simulated bi-directional SPP excitation efficiency spectrum for the Si-tip structure with the optimized geometry i.e. $h_{\text{Tip}} = 2.7 \mu m$ and $w_{\text{Cap}} = 4.6 \mu m$. For the definitions of $h_{\text{Tip}}$ and $w_{\text{Cap}}$ see Figure 5.5-a.

In a similar fashion as described in Chapter 4 a unidirectional SPP excitation can be achieved by displacing the center of the incoming beam towards one side from the center of the base (i.e. to the left to excite the SPP on the right side and vice versa) as shown in Figure 5.10-a. Figure 5.10-b
plots the unidirectional SPP excitation efficiency spectrum. It is evident in Figure 5.10-b that approximately 44.5% of the power launched by the beam can be converted to a unidirectional SPP mode. Figure 5.11 shows the extinction ration between the left and right propagating mode for a unidirectional excitation of SPP which stays above 35 dB throughout the C band of the telecom spectrum.

Figure 5.10: a) Simulate Power density profile of the unidirectional SPP excitation setup. The input beam was displaced 2.7 μm towards the left as indicated by the green arrow. The yellow arrows show the flow of the path of light. b) Simulated SPP excitation efficiency spectrum for unidirectional excitation scheme. For the calculations, the source MFD was 5 μm, the tip height and width was 2.7 μm and 4.6 μm as mentioned in the text.

Figure 5.11: Right to left side SPP extinction ratio for a source displacement of 2.7 mm towards the left as shown in Figure 5.10-a. Figure was obtained by Lumerical FDTD simulation.

5.3 Fabrication of the Oxide Capped SPP Excitation Device

After optimization of the geometry of the oxide capped SPP excitation device the attention is turned towards the fabrication of the device. A major portion of the fabrication process is similar
to the fabrication of the gabled tip near field SPP excitation setup presented in Chapter 4. I started the fabrication with a piece of \(<100>\) Si wafer and grew 300 nm of SiO$_2$ by thermal oxidation (18 mins in the Bruce Technologies Oxidation Furnace at TNFC). The fabrication of the designed device as shown in Figure 5.12 was not complete before the time of the submission of this thesis. Thereby I present the outline of the fabrication process and the portion that is already carried out in the future work section (6.1.3) of Chapter 6. Figure 5.12 depicts the schematic of the planned sample of the top Au/air interface SPP excitation scheme.

![Figure 5.12: Schematic diagram of the fabricated oxide capped Si gables tip for SPP excitation.](image)

### 5.4 Planned Characterization

Once the fabrication of the sample as depicted in Figure 5.12 is completed the characterization will be carried out using the setup depicted in Figure 4.11 in two steps as described for the SPP excitation device in Chapter 4 – measurement of the SPP coupling efficiency and measurement of the radiation pattern from the gratings that ensures the coupling of SPP modes.

### 5.5 Conclusion

In this chapter I present the design of a SPP excitation scheme developed based on the scheme presented in Chapter 5. The simulation results show a unidirectional SPP excitation efficiency of \(~49.5\%\) can be achieved using the proposed scheme. The excitation with the new scheme is less noisy since none of the stray or scattered light beneath the metal layer, but only the light from inside the tip structure can penetrate through the aperture. The critical alignment portion for the setup is already taken care of by the geometry of the device and one should only align the beam
with the large base of the tip. Furthermore, the excited SPP mode is easily accessible from the 
external environment – making the device suitable for potential applications in optical sensing. In 
the section 6.1.3 I also present the outline of the fabrication process as future continuation of the 
work which is currently under execution.
Chapter 6. Conclusion and Future Work

In this thesis, I have presented my work on the development of compact and efficient techniques of light coupling to integrated photonic circuits and sensors. As described in Chapter 1, the lack of a standard light emitting source on Si platform necessitates light to be coupled to on-chip devices from external sources via optical fibers. Such fiber-to-chip coupling comes with inherent coupling losses caused by a few reasons like mismatch of mode size/shape and the effective indices of the coupling modes. Therefore, the initial focus of my work was focused on developing fiber-to-chip light coupling techniques to Si photonic circuitry. Building on this initial investigation I then focused attention onto light coupling problems in chip-to-chip communication, plasmonic devices and sensors.

The first work presented in Chapter 2 of this thesis focuses on the development of a new bilayer, inverse taper, edge coupler for fiber to Si-photonics chip coupling with improved coupling efficiencies for both the TE and TM modes. A coupling efficiency of 1.7 dB for fiber-to-chip coupling was achieved while the proposed bilayer taper displayed > 1.5 dB improvement of coupling efficiency for both TE and TM polarizations over a conventional bilayer taper proposed by (Almeida, Panepucci, & Lipson, 2003). Furthermore, the design of the device is fully compatible to the design rule check (DRC) protocol of the commercial foundries, hence can be readily used in commercial Si photonic chips.

Next, in Chapter 3, I present a KOH etched Si micro-prism structure for beam routing in the broadside direction which can find applications in on-chip or chip-to-chip beam routing. The work was extended to an elastic Polydimethylsiloxane (PDMS) micro-prism structure on a stretchable PDMS film. A lateral pressure on the PDMS film changes the slope of the PDMS micro-prism enabling a scanning of the released beam in the broadside. Such beam routing scheme can find potential applications in inter-chip optical communication for integrated photonics. Additionally, the PDMS beam scanning technique can be useful in exciting surface plasmon polaritons at a metal/dielectric interface in visible wavelength range with high efficiency – hence the approach can be useful for SPP based sensors.

Following the PDMS beam routing mechanism, my investigations were focused to address the challenges in efficient excitation of surface plasmon polariton (SPP) modes in a compact and on-
chip setup compatible to Si platform. In Chapter 4, a gable shaped Si-tip based surface plasmon polariton (SPP) excitation scheme was developed as a possible solution to the SPP excitation problem. The Si-tip based SPP excitation scheme can convert as much as 52% of the input power to the SPP mode of an Au/SiO₂ interface at 1550 nm wavelength with a control over the directionality. The proof of concept experiment, with a large input beam demonstrated a 25% SPP excitation efficiency. Simulations which consider the effects of the fabrication imperfections of the device geometry shows good agreement with experiment and predict a 26% SPP coupling efficiency.

In the final portion of this thesis, in Chapter 5, I present the design of an SPP excitation scheme where the top portion of the gable-shaped Si-tip penetrates through an opening in a metal film and excites the SPP mode at the top Au/air interface making it more accessible by the external environment. The maximum achievable SPP coupling efficiency for this scheme is ~44.5% at the 1550 nm wavelength. Both the SPP excitation schemes presented in Chapter 4 and Chapter 5 are compact, efficient, compatible to Si platform and can find significant application in photonic circuitry (i.e. designing efficient plasmonic detectors), miniaturization of optical sensors and nonlinear plasmonics. In the next section, I suggest some probable future extensions of my work presented in this thesis.

6.1 Future Possibilities

There can be some immediate paths to extend the works presented in the thesis. In the following, I discuss the possibilities of future work on each of the projects I presented in the thesis:

6.1.1 Bilayer Inverse Taper Coupler

In Chapter 2, I have presented the characterization of the Bilayer inverse taper coupler in the C-band (1530 nm – 1565 nm) of the telecom wavelengths. However, in principal, similar edge couplers can be designed for operation in other telecom bands i.e. the O band (1260 nm – 1360 nm). The continuously growing demand of high data-rates is encouraging the exploration of the other telecom bands for career frequencies in wavelength division multiplexing (WDM) channels and design new generation of ultra-wideband photonic components for an all-band photonic transport system (Yamamoto & Sotobayashi, 2009). Therefore, an immediate step can be taken to understand the behavior of the proposed bilayer taper presented in Chapter 2 in other telecom bands than the C band. Below is a quick guideline of the steps that can be taken:
1. Run an overlap analysis of the bilayer inverse taper tip mode with a 5 \( \mu m \) mode field diameter fiber mode for both polarizations and estimate the coupling performance in the O – band of optical telecommunication.
2. Optimize the geometry of the bilayer taper per the wavelength window of interest keeping the commercial foundry DRC protocols in mind.
3. Fabricate the new designed geometry and compare to the performance of the reference inverse taper at the new wavelength window.
4. Design the device for an ultra-wideband with an acceptable performance in the broad wavelength window encompassing several telecom bands.

### 6.1.2 Broadside High Index Dielectric Beam Routing

To extend the work on the broadside beam routing idea presented in Chapter 3, research should be focused on integrating the beam routing mechanism on an SOI chip. Furthermore, a very important advantage regarding the PDMS micro-prism on the stretchable film is, PDMS is transparent to visible wavelength and similar beam routing can be achieved with visible wavelengths. The negligible absorption of PDMS at visible wavelengths opens the possibility of using a PDMS gable shaped tip for exciting SPP in the visible wavelengths as well (with similar geometry as presented in Chapter 4), an area which is not explored in the scope of this thesis. Below is a quick outline of the steps to be taken to achieve a high efficiency SPP excitation in the visible wavelengths using the PDMS tip:

1. Run a sweep of the slope angle, \( \theta \) (like Figure 4.3), but instead of a Si gable tip, use PDMS as the material and use a visible wavelength as the source wavelength.
2. Determine the deviation (\( \Delta \theta \)) of the optimized slope deviation from 54.7\(^0\) (the PDMS gable tip slope at rest position) for a maximum SPP excitation at the wavelength of concern.
3. Optimized the substrate film thickness of the PDMS capable of withholding the stress necessary to generate \( \Delta \theta \).
4. Deposit gold (or the metal of interest) on a microscope slide (glass). Then attach the PDMS film to the metal deposited surface of the glass slide such that the side that contains the tip is in touch with the metal.
5. Design a stretchable stage capable of applying a lateral stress on the PDMS film to induce the $\Delta \theta$ change in the tip slope, thus enabling an excitation of the SPP mode at the visible wavelength. A schematic of the full set up design is depicted in Figure 6.1.

### 6.1.3 Efficient SPP Excitation Scheme

As mentioned at the end of the section 5.3 of Chapter 5, here, I present the outline of the fabrication process being/to be undertaken to fabricate the sample for characterizing SPP excitation efficiency at the Au/air interface as depicted in Figure 5.12. The portion of the fabrication already carried out, hence mentioned in the past tense, is followed by the outline of the remaining portion of the process.

I started the fabrication with a piece of $<100>$ Si wafer and grew 300 nm of SiO$_2$ by thermal oxidation (18 mins in the Bruce Technologies Oxidation Furnace at TNFC). Patterns of 500 nm wide lines and square marker pads of 200 micron sides were made on a ma-N 2405 negative resist layer previously spun on top of the oxidized Si sample, using Vistec E-beam lithography unit at the TNFC fabrication facilities of the University of Toronto. As the next step oxide etch was carried out by the Oxford Instruments deep reactive ion etching (DRIE) unit at the TNFC fabrication facilities. This left the $<100>$ Si wafer surface masked by 500 nm wide lines of SiO$_2$ for the KOH wet etch. The wet etch of Si masked by SiO$_2$ lines was carried out by submerging the patterned sample in 45% KOH solution for 10 mins at 80$^\circ$C temperature. As KOH etch of Si is faster in the $<100>$ direction as compared to the $<111>$ direction, the etch creates a sidewall slanted by 54.7$^\circ$ from the edge of the mask line as shown in Figure 4.10. Therefore, as the wet etch progressed, the slanted sidewalls on both sides of the 500-nm wide SiO$_2$ mask lines created a gabled tip shaped Si taper structure with a 500-nm wide tip and 8 $\mu$m height. Then I deposited a thick (more than 12 $\mu$m) PECVD oxide on top of the fabricated Si chimneys using the Oxford
Instruments PlasmaLab System 100 PECVD. Then I planarized the top surface of the deposited PECVD oxide using chemical mechanical polishing (CMP) and polished down the oxide surface to approximately 2 μm above the Si-tip. The bottom surface of the sample (rough Si) was also polished for reducing the defused reflection while coupling light from the bottom. The planarization helps get rid of the bumps on the top surface of the oxide due to oxide deposition on a Si surface that contains gable shaped tip structures.

From this point, I needed to introduce a different set of fabrication steps as compared to the ones described in the fabrication section 4.7 in Chapter 4. Since I need to make an oxide cap structure on top of the Si-tip, another step of E-beam lithography is due to be added. Since the etch depth is at least 2.7 μm (the cap can be higher than the optimized tip height of 2.7 μm), either a resist with very high selectivity with SiO₂ or very thick resist compatible to e-beam lithography is required. I used a SU-8 (5) resist with which a thickness of ~ 5 μm was achieved with a spin speed of 1350 rpm. Then the SU-8 was patterned again with the Vistec e-beam lithography. 4.6 μm wide lines were drawn at this step of e-beam patterning. RIE (Reactive ion etching) was used to etch 5 μm high pillars over the gabled Si-tip as shown in Figure 5.5-a (using Oxford PlasmaPro 100 Cobra ICP-RIE -Si). An RIE oxide etch of 5 μm to create the oxide cap still leaves ~2 μm of oxide above the gabled tip. at this point it turned out that with existing oxide etch recipe in the RIE instrument, the remainder oxide surface was rough and not suitable for further deposition of a metal film as required for the SPP excitation. A better recipe to solve the problem is currently under development. The rest of the fabrication steps are outlined in the following:

Once the expected oxide thickness is achieved such that the gable shaped tip is housed inside the cap structure as shown in Figure 5.5-a, metal will be deposited on the sample using electron beam (E-beam) evaporation system. Now in a similar fashion as described in Chapter 4, A grating will be fabricated along with the metal deposition using lift off process. For a patterned lift off process, a second layer of negative resist (ma-N 2405) will be spun on the sample and patterned with e-beam lithography followed by metal deposition. Then lift off will be performed by rinsing the sample in acetone accompanied by undulation of the beaker. The final expected outcome of the fabrication process is depicted in Figure 5.12 in Chapter 5.

Beyond the fabrication plan outlined above, the proposed SPP excitation schemes as mentioned in Chapter 4 & Chapter 5, can find applications in numerous fields of photonics. Considering the
general focus of this thesis – *efficient coupling of light to photonic circuitry*, the proposed SPP excitation schemes can perform an important role in designing vertical interconnects as well as plasmonic detectors with high efficiency at 1550 nm. The design of on-chip plasmonic detectors are based on the idea of internal photo-emission (IPE) process. The IPE can be enhanced by the efficient excitation an SPP mode at the Schottky interface between a metal and a semiconductor. The compact size of the proposed scheme in Chapter 4 & Chapter 5 and the capability of efficiently converting power to an SPP mode can be effectively used to generate efficient IPE entailing a successful detection of incoming photons from the base of the gable Si-tip. One should engineer the device geometry showed in Figure 4.9 -a, or Figure 5.12 to excite an SPP mode at an interface between the gold layer and a doped semiconductor layer to create a Schottky contact. Furthermore, such high efficiency SPP excitation can generate intense field localization along the interface which can be used for studying nonlinear plasmonic phenomena.

6.1.4 Si Gable-tip waveguide couplers

In Chapter 4, an efficient SPP excitation technique was demonstrated which, was then further extended to another topology of SPP excitation in Chapter 5 making it more suitable for SPP based applications. A further analysis of the setup proposed in Chapter 5 (Figure 5.12) shows that such a scheme can be useful to couple light to a Si waveguide as well as exciting a SPP at a nearby Au/air interface. Additionally, attaching the bilayer inverse taper (presented in Chapter 2) to the start of the waveguide next to the Si tip as shown in Figure 6.2 can increase the coupling efficiency. In this section, I propose the initial device design and some preliminary simulation results for coupling light from an external off-chip source to a Si waveguide on a Si platform combining the device ideas presented in Chapter 2 and Chapter 5. This design can be easily extended to the conventional SOI platform for Si photonics with some modification of the geometry.
Figure 6.2: Schematic diagram of light coupling scheme to Si waveguide using Si gable tip. a) Cross section & b) 3D view (not drawn to scale).

Figure 6.2 shows the proposed device setup for the Si gable-tip source-to-waveguide coupling scheme. Like the setup in Figure 5.12, light is directed to the waveguide-under-concern through a gable shaped Si tip, the apex of which emerges out from a lower index medium (SiO$_2$, typically the bottom oxide layer of an SOI wafer). Now in this case, instead of a metal layer on top of the oxide layer, a single mode Si waveguide sits in front of the protruding tip of the gable shaped Si structure. The entire tip-waveguide geometry can then be coated with another layer of SiO$_2$ acting as the top oxide layer of an SOI device (shown by the green layer in Figure 6.2). Also, to increase the coupling efficiency, the bilayer inverse taper coupler demonstrated in Chapter 2 is attached to the front of the Si waveguide, facing the Si tip. As shown in the schematics in Figure 6.2, light is fed to the base of the gable-tip, deflected by the slanted wall of the tip towards the taper front facet and then later, coupled to the waveguide attached to it.

Figure 6.3: Simulated coupling efficiency to the TE and TM mode of a Si waveguide using the setup shown in Figure 6.2. The result was obtained from a full wave 3D Lumerial FDTD simulation. The tip height was 11.5 $\mu$m. The Gaussian source had a 5 $\mu$m mode field diameter which was displaced by 2.5 $\mu$m towards the left from the center of the gable tip base. The bottom oxide thickness was 15.39 $\mu$m. These parameters can be changed to match the structure to a conventional SOI platform.
The preliminary simulations in Lumerical FDTD (Lumerical Solutions, Inc., n.d.) shows a ~ 27% coupling efficiency can be achievable for a TE mode coupling to a Si waveguide while a ~ 25% coupling efficiency achievable for the TM mode using the scheme (Figure 6.2). Additionally, the device shows a broad-band operation in the optical telecom wavelengths. Further improvement can be possible by optimizing the geometrical parameters of the proposed setup. The geometry for obtaining the results in Figure 6.3 is given in the figure caption. Also, one can change the height/thickness of the bottom oxide layer (and the tip height accordingly) to match the geometry to be compatible with the SOI platform.

The major advantage this proposed coupling scheme can provide is increasing the misalignment tolerance. The tedious fine alignment portion of the coupling process – aligning the 10 μm fiber to the 220-nm height guiding layer of a SOI device, is taken-care-off by the geometry of the coupling scheme. Although the results of the current simulation do not offer the state-of-the-art coupling efficiency numbers, I believe this can be significantly improved by further optimization of the geometry of the gable tip structure as well as the inverse taper.


Appendix

Appendix A. Recipes

A.1. ZEP 520

ZEP is a positive tone electron beam resist with high resolution and excellent dry-etching resistance

Spread thickness: 300-400 nm

Characteristics:

- Positive tone
- High resolution
- High sensitivity
- Dry etch resistance comparable to most positive photo resists

Resist Name | ZEP 520 A
--- | ---
Storage | 10°C – 27°C
Surface Preparation | Acetone and then IPA (Iso-Propyl Alcohol) rinse in ultrasound for 3 mins each, then dehydration bake for 3 mins
Spin Speed | 4000-5000 rpm for 1 min
Thickness | 350 nm
Pre-bake | 180°C for 3 mins
Exposure | Dose 250 μC/cm², 100 kV
Develop | ZED N50, 1 min
MIBK : IPA 1:9 mixtures | 30 seconds
Dry | N₂ blow-dry
Resist Stripping | ZDMAC rinse in ultrasound for 3 mins, then Oxygen plasma ashing for 5 mins @ 180 Watt power
A.2. Ma-N 2405

Ma-N 2405 is a negative tone electron beam resist with low resolution and high dry-etching resistance.

Characteristics:

- Negative tone
- Electron-beam and UV (Ultra Violet) sensitive
- Low resolution
- Good thermal stability of the resist patterns
- High dry and wet etch resistance
- Easy to remove
- Not sensitive to white light

<table>
<thead>
<tr>
<th>Resist Name</th>
<th>Ma-N 2405</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>18° – 25° C</td>
</tr>
<tr>
<td>Surface Preparation</td>
<td>O₂ Plasma Ash, Acetone and then IPA rinse in ultrasound for 3 mins each, then dehydration bake for 3 mins, HMDS coat for Si or SiO₂ substrate</td>
</tr>
<tr>
<td>Spin Speed</td>
<td>4000-5000 rpm for 1 min</td>
</tr>
<tr>
<td>Thickness</td>
<td>350 nm</td>
</tr>
<tr>
<td>Pre-bake</td>
<td>90° C for 3 mins</td>
</tr>
<tr>
<td>Exposure</td>
<td>Dose 250 μC/cm², 100 kV</td>
</tr>
<tr>
<td>Develop</td>
<td>Ma-D 525, 4 mins</td>
</tr>
<tr>
<td>Rinse</td>
<td>DI water 5 mins</td>
</tr>
<tr>
<td>Dry</td>
<td>N₂ blow-dry</td>
</tr>
<tr>
<td>Resist Stripping</td>
<td>Acetone, Oxygen Plasma</td>
</tr>
</tbody>
</table>

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A.3. SU-8 2002

SU-8 2002 is a negative tone resist mostly used in photolithography. Therefore, the resist is sensitive to exposure to visible light. Hence extra care should be taken while handling samples coated with resist. A good practice is to carry the sample holders wrapped by aluminum foil paper when taken outside the cleanroom. Also, if there is an alignment step in the lithographic process extra care should be given while aligning so that the important areas in the sample is not exposed to the white light in the optical microscope for alignment beside the Vistec E-beam system in TNFC.

Characteristics:

- Negative tone
- Electron-beam and UV sensitive
- Low resolution
- Good thermal stability of the resist patterns
- High dry and wet etch resistance
- Difficult to remove after a few days of exposure
- Sensitive to white light

<table>
<thead>
<tr>
<th>Resist Name</th>
<th>SU-8 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage</strong></td>
<td>18° – 25° C</td>
</tr>
<tr>
<td><strong>Surface Preparation</strong></td>
<td>O₂ Plasma Ash, Acetone and then IPA rinse in ultrasound for 3 mins each, then dehydration bake for 3 mins, HMDS coat for Si or SiO₂ substrate</td>
</tr>
<tr>
<td><strong>Spin Speed for spreading</strong></td>
<td>500 rpm for 30 sec.</td>
</tr>
<tr>
<td><strong>Spin Speed for coating</strong></td>
<td>1350-1450 rpm for 1 min</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>~ 2.5 microns</td>
</tr>
<tr>
<td><strong>Pre-bake</strong></td>
<td>95° C for 2 mins</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>Dose 8.5 μC/cm², 100 kV (for a bottle a year after expiry date)</td>
</tr>
</tbody>
</table>
**Post bake**

95° for 2 mins. If the written pattern does not become visible, bake again for another 2 mins. Keep on repeating until patterns appear.

**Develop**

SU-8 developer, 1 mins

**Rinse**

DI water 30 s

**Dry**

N₂ blow-dry

**SU-8 (5)**

SU-8 5 is another version of the resist with a higher viscosity, therefore a thicker resist layer is created after coating. The recipe for the SU-8 5 resist is almost the same as the SU-8 2002 resist except for the dose, which should be changed to 9.5-10 μC/cm². Also, the pre- and post-bake process should be done with a ramp of temperature:

Pre-bake: 2 mins at 65° C and then 5 mins at 95° C.

Post-bake: 1 mins at 65° C and then 1 min at 95° C.

For more information, the reader can check the [Micro-Chem SU-8 5 data-sheet](#).
### A.4. HSQ (Fox-15) Flowable Oxide Resist

HSQ is a negative tone electron beam resist with high resolution and high dry-etching resistance. For use on SOI, I used a diluted version of HSQ – Fox 15: MIBK (1:1) mixture.

**Characteristics:**

- Negative tone
- Electron-beam sensitive
- High resolution
- Good thermal stability of the resist patterns
- High dry and wet etch resistance
- Easy to remove
- Not sensitive to white light

<table>
<thead>
<tr>
<th>Resist Name</th>
<th>Ma-N 2405</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>Less than 80°C</td>
</tr>
<tr>
<td><strong>Surface Preparation</strong></td>
<td>O₂ Plasma Ash, Acetone and then IPA rinse in ultrasound for 3 mins each, then dehydration bake for 3 mins, HMDS coat for Si or SiO₂ substrate</td>
</tr>
<tr>
<td>Spin Speed</td>
<td>4000-5000 rpm for 1 min</td>
</tr>
<tr>
<td>Thickness</td>
<td>350 nm (For pure HSQ this ness is ~ 900 nm)</td>
</tr>
<tr>
<td>Pre-bake</td>
<td>100°C for 3.5 mins</td>
</tr>
<tr>
<td>Exposure</td>
<td>Dose 900 μC/cm², 100 kV, 5nA current</td>
</tr>
<tr>
<td>Develop</td>
<td>CD-26, 3 mins</td>
</tr>
<tr>
<td>Rinse</td>
<td>DI water 5 mins</td>
</tr>
<tr>
<td>Dry</td>
<td>N₂ blow-dry</td>
</tr>
<tr>
<td><strong>Resist Stripping</strong></td>
<td>Hardened resist is effectively oxide. Should be removed using dry (plasma) or wet (BOE) oxide etch</td>
</tr>
</tbody>
</table>