Sub-wavelength Silicon Photonic Devices for Optical Interconnect Networks

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Sub-Wavelength Silicon Photonic Devices for Optical Interconnect Networks

by

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B.S. University of Rochester, 2005
M.S. University of Colorado, 2011

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Electrical Computer and Energy Engineering
2013
This thesis entitled:
Sub-Wavelength Silicon Photonic Devices for Optical Interconnect Networks
written by Eric F. Dudley
has been approved for the Department of Electrical Computer and Energy Engineering

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Wounjhang Park

________________________
Prof. Alan Mickelson

Date ____________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
As our demand for information grows, so too does the demand for networks capable of handling this flood of data. Conventional on-chip electrical networks are approaching their limits in terms of latency, power consumption and data rates and will need to be replaced with new technology in the near future. Photonic networks promise great improvements over electrical networks, but several key challenges still hinder their widespread deployment.

This thesis focuses on addressing the problem of encoding and routing data inside integrated optical communication networks. This is accomplished through electrically driven optical switches or modulators that are able to produce a binary optical data stream from a binary electrical input signal. The primary metrics used to evaluate the performance of these devices are spatial footprint, modulation-switching speed, operating voltage and power consumption per bit. Secondary concerns are device bandwidth, CMOS compatibility, tolerance to fabrication errors and device losses. In this thesis, we present a theoretical design for an electrically driven optical switch utilizing hybrid silicon-insulator-metal waveguides with a 30 $\mu m^2$ footprint, 57 Gbit/s switching speed, 2.6 fJ/bit power consumption and 1V operation. We also present experimental confirmation of the optical properties of hybrid silicon-insulator-metal waveguides which form the basis of this design.
Acknowledgements

I would first like to thank my advisor, Dr. Wounjhang Park for his unwavering dedication to my education and graduate school success. Even though the going was tough at times he has always been incredibly supportive, willing to listen to my problems and very constructive in both his advice and his criticisms. He pushed me to go beyond what I thought I could achieve and none of this would have been possible without his guidance and assistance.

I am particularly grateful to Dr. Yonghao Cui for all his assistance in fabricating and testing my hybrid waveguide devices. Without his help none of this would have been possible and I am extremely fortunate to have had the assistance of such a skilled, knowledgable and generous person.

I would also like to thank Xi Chen and Zefram Marks for their help in fabricating and testing my devices. Xi was kind enough to let me use his measurement set up and train me in its use, gave me access to and trained me in the use of a clean room and was always willing to answer my questions on materials and fabrication. Zefram’s expertise in nano-fabrication and the Colorado Nanofabrication Facilities was invaluable in completing this project.

Next, I would like to thank the members of the EMT/NANO project: Dr. Won Park, Dr. Dejan Filipovic, Dr. Li Shang, Dr. Brian Schwartz, Xi Chen, Houngyu Zhou, David Espinoza, Moustafa Mohammed and Zheng Li. The project was a wonderful collaboration that resulted in a number of publications, a great increase in my knowledge on a wide range of subjects and eventually the idea which inspired the work for this dissertation.
Finally, I would like to thank all my friends and family for being so supportive and wonderful through this long and stressful process.
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Chapter 1

Introduction

1.1 Motivation and Applications

We live in the age of big data and big problems that require substantial computational resources to address. Increasingly computationally capable systems are needed to address problems in quantum physics, weather forecasting, climate research, oil and gas exploration, molecular simulation and physics modeling. Advances in semiconductor technology are the primary mechanism for pushing the boundaries of computational performance.

The U.S. semiconductor industry is one of the great successes of the twentieth century. The success of this industry is driven by its phenomenal rate of innovation and ability to continuously deliver new technologies. The progress of the semiconductor industry was quantified in a paper by Gordon Moore in 1965, in which he observed that the number of components that could be incorporated per integrated circuit would increase exponentially over time [1]. This observation has become known as Moore’s law, and since 1970 the number of components per chip has doubled every two years as shown in figure 1.1.

The increase in processor capability has been driven primarily by circuit miniaturization through down scaling of the transistor. The number of transistors per chip has been increasing in compliance with Moore’s law for over 40 years. This is achieved primarily though reducing the critical dimensions of the on-chip components. The primary component responsible for computational power scaling is the transistor. The transistor forms the backbone of all modern electronic devices and the down scaling of its critical dimensions has
Figure 1.1: This diagram illustrates the microprocessor industry’s compliance with Moore’s law. It plots CPU transistor count against time on a semi-log scale.
been the primary driving force behind the continued increases in processor capability.

The demand for higher data rates and increased processor power has been driving the explosion in miniaturization of on-chip components in the semiconductor industry for many years. However, the power consumption of each device has not been downscaling at the same rate as the physical dimensions of the devices. This led to a heat sinking problem in single core systems which has so far proven intractable. Due to the heat sink limitations of single core processors, the trend to miniaturize the individual components of semiconductor based computer processor units (CPUs) has been superseded in recent years by a move to parallel computing to increase transistor counts while mitigating heat removal issues. Multicore systems are the new paradigm in high performance computing. Processor-core scaling has become the dominant mechanism to keep up with the ever increasing demand for computational power. Parallel computing has a number of drawbacks over single CPU based machines. One serious issue is the added complexity of the software required to enable efficient parallel processing. Data management and software parallelization are difficult problems that hinder the usefulness of many core computers. The other major problem is the issue of network interconnects to enable data transfer between the cores. The most widespread technology used in on-chip interconnect networks is copper based electrical interconnects. While these networks have succeeded in scaling to meet the demand for bandwidth, the limitations of copper based interconnects are becoming increasingly obvious as interconnect densities rise to keep pace with processor core scaling. One of the major limitations of copper (or any electrical) interconnects is that the resistance and time constant of wires transporting electrical data increases as device dimensions are scaled down, leading to high energy costs for transporting information in highly integrated systems. In addition, electrical interconnects are reaching their practical limits in terms of loss, dispersion, cross-talk and bandwidth [2] [3]. Recent increases in the bandwidth of electrical interconnects to keep pace with the demands of data hungry systems such as super computers have only been achieved at the expense of increased latency and power consumption [4].
In time, optics will replace electrical interconnects just as fiber networks have begun to replace telephone lines as the primary mechanism for transporting data over long distances. Optical networks already provide fast, reliable data transport over medium to long distances (on the scale of meters to kilometers), but adapting these networks to the millimeter and smaller scales has proven to be elusive [5]. Optical technology will spread to very short distances as the technology becomes more cost effective, reliability issues are ironed out and the demand for increased bandwidth and decreased power consumption drives innovation in the realms of micro and nano photonics. The primary applications for optical interconnects are high performance computing, data center and mobile-to-server interconnects and even personal electronics. Optical interconnects potentially have several major advantages over their electrical counterparts. First, they enable the separation of electronic devices, allowing for the optimization of the chip layout while retaining high data rates. In addition, optical networks have a number of well known advantages such as lower levels of electromagnetic interference, reduction in cable length, weight and possibly cost and substantial savings in both energy used to transport data and energy lost to heat. Optical signals can also retain precise clock and signal timing [4], provide a more flexible design platform that could reduce the interconnect density, allow for signal multiplexing and reduce latency.

Of particular interest for computational applications are the optical interconnect’s promise for reducing the power consumed by the interconnect and latency reduction. Power consumption in electrical interconnects is an important concern for large scale systems since the amount of heat that can be removed from the chip in a cost effective manner is expected to remain constant in the foreseeable future [3]. The energy converted to heat in an electrical interconnect scales super-linearly with the number of connections within the network. The number of connections within an electrical interconnect network scales geometrically with the number of cores, since each core needs a point-to-point connection to every other core. Due to this constraint on the interconnect, increasing the power of a computational system by adding cores not only causes more connections, but also increases the density of the
network forcing the individual connections to become smaller. Unfortunately, down scaling of the wires used in electrical interconnects increases their resistance since the resistance of a current carrying wire is given by: 

\[ R = \rho \frac{L}{A} \]

where \( \rho \) is the resistivity of the wire material, \( L \) is the length and \( A \) and is the cross sectional area of the wire. The increased resistance results in each connection generating an increasingly large amount of heat as it is down scaled. By contrast, the energy cost for optical interconnects is determined by the size of the transmitter and receiver, and could be decreased with the device design [6]. At 130 nm half-pitch CMOS fabrication, approximately 51% of microprocessor power was consumed by the interconnect, with a projection that without changes in design philosophy, in the next five years up to 80% of microprocessor power will be consumed by the interconnect [2]. Optical interconnects, by contrast can theoretically have sub-linear power scaling with processor count [7]. Due to the critical nature of the interconnect energy scaling problem, low power optical interconnects are in extremely high demand for a wide variety of application.

Another crucial advantage of optical networks over electronic ones is in the area of latency. Latency is a measure of the time-delay experienced inside a system between transmitting and receiving a signal. Electrical signals are limited by the drift velocity of the electrons inside a wire which in turn is dependent on the length of the wire and the voltage drop between its ends: 

\[ V_d = \mu \frac{V}{L} \]

where \( \mu \) is the electron mobility inside the material of the wire, \( V \) is the voltage drop between the start and end of the wire and \( L \) is the length of the wire. This means that to increase the speed that signals travel through an electrical wire, the voltage and/or the electron mobility must be increased. Mobility is generally a function of the material and higher voltage can be damaging to delicate electronics as well as contributing to higher energy loss through resistive heating. This fundamentally limits the speed at which electrical signals can propagate and contributes to latency in the network. By contrast, optical networks propagate their signals at the speed of light. This is the upper limit for how quickly electromagnetic signals can be propagated and therefore optical networks automatically have the smallest possible latency for their configuration.
In addition to power savings and latency reduction, optical interconnects might be used with multiple wavelengths in a single waveguide (wavelength-division multiplexing (WDM)) to provide not only higher bandwidth density for global interconnects, but also in combination with on-chip, voltage variable gratings to provide selective routing possibilities that can be used for radically different signal processing functions than those currently available [2]. This provides the promise of dramatically increased bandwidth, even while reducing the number of connections necessary to carry all of the information [8].

In order to achieve all of these lofty goals, optical networks need to be both miniaturized and integrated into existing computer architectures. The most promising technology towards this end is silicon photonics. Silicon photonics is the platform of choice for optical interconnects for a variety of reasons including its low fabrication costs, compatibility with CMOS technology, high density integrability, robust materials and excellent performance. However, silicon is a non-ideal material for optical applications due to its indirect bandgap and centro-symmetric crystal structure. The indirect bandgap makes silicon an inefficient light source and the centro-symmetric crystal structure causes it to have a zero linear electro-optic or Pockel’s coefficient. Despite these limitations, Si can be an extremely useful material an alternate light sources and detectors are employed. Advanced, low-cost bipolar and CMOS technologies can be applied for sophisticated signal processing functions as well as light sensing functions in visible and near infrared wavelength regions [9]. Despite these limitations, silicon photonic networks must be able to perform a variety of functions, requiring a wide array of different passive and active devices to generate, bend, split, filter, switch, delay and detect optical signals. One of the most crucial devices necessary for the successful operation of a photonic network is an optical modulator.

1.2 Optical Modulation in Silicon

An optical modulator is a device that alters the amplitude, phase and/or polarization of an optical beam. Optical modulation is one of the main required functionalities for any
optical interconnect solution. The primary purpose of an optical modulator in a photonic network is to modulate the light source. This modulation can be done either directly or externally, but external modulation offers several advantages over direct modulation: the optical source can be relatively inexpensive and its operation does not need to be compromised by direct modulation, modulation speeds can be higher, direct phase modulation is possible, and optical isolation and wavelength stabilization need to be performed only once for the entire system. Furthermore, a single light source can feed multiple channels via individual modulators, thus reducing the total power budget of the system [10]. It is also highly desirable for an optical modulator to be driven by an electrical input since this allows for easy integration with existing technology, fast response and synchronization with the underlying electrical components on the chip. Electrically driven optical modulators are separated into two main categories: electro-refractive and electro-absorptive. Electro-refractive modulators operate by using an applied electric field to change the real part of the refractive index of a material (Δn) while electro-absorptive modulators change the imaginary part of the index (Δκ). κ is related to α, the linear absorption coefficient, by the relation $\kappa = \frac{\alpha \lambda}{4\pi}$ where $\lambda$ is the optical wavelength.

1.2.1 Electro-Absorptive Modulators: Free Carrier Injection

Intrinsic crystalline silicon has very limited opto-electronic uses due to its lack of the Pockel’s effect deriving from its centro-symmetric crystal structure. Also, the Franz-Keldysh effect and Kerr effect are both too small and limited for use in active opto-electronic devices such as optical modulators [9]. Instead, charge carrier effects must be used to induce an electro-absorptive response from crystalline silicon. The most common charge carrier effect used to create optical modulators in silicon is free carrier absorption from carriers injected into an intrinsic silicon opto-electronic element by a p-i-n junction.

In an intrinsic semiconductor, the number of conduction band electrons always equals the number of valence band holes. This charge balance can be deliberately disturbed if the
crystal is doped, i.e., if different atoms (impurities) are introduced that replace some of the original atoms forming the semiconductor lattice. These impurities generally have a different number of electrons than the atoms they are replacing.

In a pure silicon crystal, each Si atom has four valence electrons that can form Lewis octets with four other atoms. When an occasional electron is shaken loose by thermal excitation or a crystalline defect, silicon becomes a weak conductor of electricity. Si can be doped with phosphorus (P), nitrogen (N) or arsenic (As) atoms, which have five valence electrons. The fifth electron is not needed for bonding and becomes available as a current carrier. This is effectively a free electron with a binding energy similar to that of hydrogen.

\[
E_d = \frac{e^4 m_e}{2\hbar^2 \epsilon_0^2}
\]  

(1.1)

Where \(m\) is the effective mass of an electron in Si. This energy is on the order of a few 10s of meV which allows the P atom to “donate” an electron to the crystal. This changes the material from an insulator to a poor conductor at room temperature. A material doped with donors such as P, is referred to as “n-type”.

Similarly, if the Si is replaced by boron (B), aluminum (Al) or gallium (Ga), the boron acts as an acceptor. B has one less valence electron that Si and requires one of the neighboring Si atoms to donate a valence electron to form a crystal bond. The B “accepts” the electron, becoming negatively ionized and the missing electron in the Si valence band is referred to as a hole. A material doped with acceptors is called “p-type”. The binding energy \(E\) of the B atom is given by:

\[
E_d = \frac{e^4 m_h}{2\hbar^2 \epsilon_0^2}
\]  

(1.2)

Where \(m\) is the hole effective mass of silicon.

At ambient temperatures, the carrier concentrations in intrinsic, technologically important semiconductors, such as Si, GaAs, InP, GaN, and CdTe, are fairly small. For example,
in intrinsic Si it is on the order of $10^{10} \text{cm}^{-3}$. As a result, intrinsic materials are not widely used in device technology. Instead, they are appropriately doped either during the growth of bulk crystals or during the deposition of epitaxial layers. These materials are referred to as extrinsic semiconductors and the doping is global in nature [11].

P-i-n diodes can be used to inject free carriers into the intrinsic region of the diode by applying a forward bias across the junction. This minimizes the potential barrier between the p and n-type semiconductors and allows current to flow from the n region to the p region. This causes an increase in the free carrier concentration in the intrinsic region while the forward bias is applied. This process can be halted by turning off the forward bias and applying a reverse bias instead. This shifts the energy bands of the n-type and p-type semiconductors further apart and sweeps the free carriers out of the intrinsic region.

The speed at which carriers can be injected into the intrinsic region is governed by the following equation:

$$\frac{dQ(t)}{dt} = i(t) - \frac{Q(t)}{\tau}$$  \hspace{1cm} (1.3)

Where $Q(t)$ is the carrier charge in the junction, $\tau$ is the carrier recombination lifetime and $i(t)$ is the current flow through the junction. If $i(t)$ is assumed to be constant, the solution to equation 1.3 is:

$$Q(t) = i \tau (1 - e^{\frac{t}{\tau}})$$  \hspace{1cm} (1.4)

The charge injection rate starts high and decreases exponentially. As a result, most of the carriers of the steady state charge would be injected very shortly after the forward bias is applied. The charge injection rate is also proportional to the current across the diode. The solution for the backwards bias condition is:

$$Q(t) = (Q_0 + I_R \tau) e^{\frac{t}{\tau}} - I_R \tau$$  \hspace{1cm} (1.5)
The time required to sweep the carriers out of the intrinsic region is:

\[ Q(t) = 0 \implies t_s = \tau \ln(1 + \frac{Q_0}{I_{RT}}) \quad (1.6) \]

Where \( Q_0 \) is the amount of charge present initially in the intrinsic region [12].

Charge injection is the principle mechanism for controlling free carrier absorption in silicon. The speed at which sufficient quantities of carriers can be injected and swept out of the active region of the device determines the speed at which it can operate.

The amount of carriers that need to be injected is related to the free carrier absorption:

\[ \Delta \alpha = -\frac{e^3 \lambda_0^2}{4\pi^2 c^2 \varepsilon_0 n} \left( \frac{N_e}{\mu_e (m_e)^2} + \frac{N_h}{\mu_h (m_h)^2} \right) \quad (1.7) \]

which leads to a refractive index change through the Kramers-Kronig relation which relate \( n \) to \( \kappa \) and vice versa. The same relations hold for \( \Delta n \) and \( \Delta \kappa \). The Kramers-Kronig relation is given by [13]:

\[ n(\omega) = 1 + \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\kappa(\omega')}{\omega' - \omega} \, d\omega' \quad (1.8) \]

\[ \kappa(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{n(\omega') - 1}{\omega' - \omega} \, d\omega' \quad (1.9) \]

\[ \Delta n = -\frac{e^3 \lambda_0^2}{8\pi^2 c^2 \varepsilon_0 n} \left( \frac{N_e}{m_e} + \frac{N_h}{m_h} \right) \quad (1.10) \]

where \( e \) is the electronic charge, \( c \) is the velocity of light in vacuum, \( \mu \) is the carrier mobility, \( m \) is the effective mass, \( n \) is the refractive index and \( \lambda_0 \) is the free space wavelength [13].

In silicon, at \( \lambda_0 = 1.55 \mu m \), these expressions are:

\[ \Delta \alpha = 8.5 \times 10^{-18} \Delta N_e - 6.0 \times 10^{-18} \Delta N_h \quad (1.11) \]

\[ \Delta n = -8.8 \times 10^{-22} \Delta N_e - 8.5 \times 10^{-18} (\Delta N_h)^{0.8} \quad (1.12) \]
It should be noted that the refractive index will increase when carriers are depleted from doped material. Conversely, the index will decrease when carriers are injected. The modulation is polarization independent. In the injection case, the switch-off time will probably be limited by minority carrier lifetime (ns to µs). However, the depletion mode is expected to offer much faster response times, possibly in the picosecond range, because of carrier sweep out. The inherent on/off response times of electrorefraction are subpicosecond. The response in practice is limited by the RC time constants of the electrooptic device [14].

For integrated optical components, footprint or device size is very important since integrated networks tend to be quite dense. This means that the size of the optical component must be kept to a minimum. To achieve modulator function, the device must be able to impart a π phase shift on a beam of light passing through the active portion of the modulator. The most common setup for constructing an optical modulator based on free carrier absorption is to construct a Mach-Zehnder interferometer where one arm can be injected with free carriers from a p-i-n diode.

The phase delay experienced by an optical wave passing through an arm of the Mach-Zehnder is given by:

$$\Phi = \frac{2\pi \Delta n L}{\lambda_0}$$

(1.13)

where L is the length of the arm. If the phase delay between the reference arm and the modulator arm is an odd multiple of π the two waves will interfere destructively when they are recombined. This results in a transmission null which can be interpreted as a binary zero. If the two waves emerge in phase (even multiples of π phase delay), they will interfere constructively to produce a binary 1.

The main limitations of this kind of modulator are carrier transport time, required operating voltage, device footprint and absorption of the optical signal by the free carriers.

All of these limitations are coupled together. To achieve a small device footprint and fast operating speed, a large number of carriers must be injected into the active region of the
device in a short amount of time. This requires a high bias voltage that can be modulated very quickly. To achieve an arm length of 100µm, the $\Delta n$ in the modulator arm of the Mach-Zehnder must be:

$$\Delta n = \frac{\lambda_0}{2nL} = \frac{1550\text{nm}}{2(3.44)(100\mu\text{m})} = 2.25 \times 10^{-3}$$

Equation (1.14)

Which corresponds to an injected carrier density of $2.5 \times 10^{18} \text{cm}^{-3}$. This is accompanied by an increase in the absorption of $21.5 \text{cm}^{-1}$ which causes a 9.5 dB loss during the traversal of the arm.

Injecting $2.5 \times 10^{18}$ carriers into the device and then sweeping them out at a high rate is not a simple matter. The time required to inject this many carriers is given by equation 1.4 and is very fast, but sweeping the carriers out is a slower process. The time required to sweep the carriers out of the device is given by equation 1.6. For a modulation rate of 10GHz, a carrier concentration of $2.5 \times 10^{18} \text{cm}^{-3}$ and a carrier damping time $\tau_p \approx 0.5 \mu\text{s}$ [16], the required current passing through the p-i-n diode is 4mA which is somewhat high for integrated semiconductor applications.

Despite having a number of limitations, electro-optical modulators in silicon have been successfully created using free carrier injection from p-i-n diodes with modulation rates up to 18 Gb/s [62] and continue to be an active area of research.

1.2.2 Electro-Refractive Modulators: Pockel’s Effect

Two main factors make free carrier injection a non-ideal platform for optical modulators: loss due to electro-absorption and slow modulation speeds. Fortunately, electro-refractive modulators can be constructed using Pockel’s effect which does not induce extra loss into the system and many electro-optic materials have response times on the order of femtoseconds - orders of magnitude faster than injecting and sweeping carriers in to and out of the intrinsic region of a PIN junction. Unfortunately, crystalline silicon has no second order non-linearity, also known as Pockel’s coefficient or the electro-optic coefficient.
The good news is that there are ways of integrating electro-optic materials into silicon photonic devices [19] [20] [21] [22] [23], but it requires some extra work. The benefits of using electro-optic (EO) materials are numerous however and devices based on integrating silicon photonics with electro-optic materials show great promise for constructing fast and efficient optical modulators.

In order to understand the operation of EO devices, we must first analyze them using non-linear theory. We begin with Maxwell’s equations [24]:

\[ \nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt} \]  
\[ \nabla \times \mathbf{H} = \frac{d\mathbf{D}}{dt} + \mathbf{J} \]  
\[ \nabla \cdot \mathbf{D} = \rho \]  
\[ \nabla \cdot \mathbf{B} = 0 \]

where \( \mathbf{E} \) is the electric field, \( \mathbf{D} \) is the electric displacement field, \( \mathbf{B} \) is the magnetic field, \( \mathbf{H} \) is the magnetizing field, \( \mathbf{J} \) is the current density and \( \rho \) is the charge density. In addition, we consider the constituitive equation \( \mathbf{D} = \mathbf{E} + P_L + P_{NL} \) where \( P_L \) is the linear polarization response and \( P_{NL} \) is the non-linear polarization response of the material. We can write the polarization response of the material as:

\[ P_{total} = m + \epsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + ...) \]

where \( m \) is the permanent dipole moment, \( E \) is the electric field, \( \chi^{(1)} \) is the linear polarizability and \( \chi^{(2)}, \chi^{(3)}, \ldots \) are the second, third and so forth non-linear polarizability coefficients of the material. In this analysis, we are primarily concerned with \( \chi^{(2)} \), the second order non-linear polarizability coefficient which is responsible for the linear electro-optic effect also known as Pockel’s effect as well as optical rectification, second harmonic generation and parametric oscillation [24]. The linear electro-optic effect manifests as a change in the re-
fractive index of the material proportional to the applied electric field and can be expressed as:

\[ P_i(\omega) = 2 \sum_{jk} \chi^{(2)}_{ijk}(\omega)E_j(\omega)E_k(0) \] (1.20)

and the change in refractive index with applied field can be found using the following equation [24]:

\[ \Delta n = -\frac{1}{2}rn_0^3E \] (1.21)

Where \( n_0 \) is the unperturbed refractive index of the material, \( r \) is Pockel’s coefficient and \( E \) is the applied electric field.

\( \chi^{(2)} \) is identically equal to zero in materials with a centro-symmetric crystal structure such as crystalline silicon, but can be quite high in non-centrosymmetric materials such as lithium niobate, gallium arsenide and certain polar dye molecules used to dope polymers to give them electro-optic properties. These EO polymers are excellent candidate materials for integration into silicon photonic electro-refractive devices. In the following chapter, we will examine one class of device, known as gap waveguides, that allows electro-optic materials to be integrated onto a silicon photonic platform.

1.3 Thesis Outline

The outline of the thesis is as follows: Chapter 2 describes the theory governing the operation of gap waveguides and details the done work designing, fabricating and testing those structures. The discussion includes an analysis of sub-wavelength light confinement using dielectrics and explores a range of passive and active devices using these waveguides. Also included is a discussion of the limitations of gap waveguides and how these issues led to the adoption of hybrid waveguides. Chapter 3 describes the theory governing the operation of hybrid waveguides as well as the design and operation of directional couplers.
and electro-optic switches based on a hybrid waveguide platform. It offers an analysis of hybrid mode theory using optical coupled mode theory as well as an analysis of the behavior of two coupled symmetric hybrid waveguides. The chapter concludes with the design of an electro-optic switch using hybrid waveguides as well as an analysis of its operation from both an optical and electrical perspective. Chapter 4 describes the work done to fabricate hybrid waveguides as well as the experiments and results conducted to confirm the theory underlying their design and demonstrate proof of concept for a hybrid waveguide electro-optic switch. Finally, chapter 5 offers conclusions drawn from this work as well as possible future directions for hybrid waveguides.
2.1 Gap Waveguide Theory

Gap waveguides are a novel kind of waveguide displaying an unusual form of optical mode guidance wherein the mode is confined primarily to a low index region confined between two high index slabs. In addition to this “Inverted” guidance, gap waveguides are also capable of confining light far below the diffraction limit which usually limits the scale of conventional waveguides. Unlike other sub-wavelength light confinement schemes [25] – [29], gap waveguides can enhance and confine the optical mode in the low-index slot even when light is guided by total internal reflection (TIR) and without the inclusion of lossy metals.

This phenomenon can be explained using electro-magnetic theory. For a high-index-contrast interface, Maxwells equations state that to satisfy the continuity of the normal component of electric flux density $D$, the corresponding electric field must undergo a large field discontinuity at the interface with a much higher amplitude in the low-index side. Gap waveguides use this discontinuity to strongly enhance and confine light in a nanometer-wide region of low-index material. This highly confined mode presents as an eigenmode of the gap waveguide system and behaves in a similar manner to other strongly guided optical modes [30].

For a slot waveguide structure as seen in figure 2.1, consisting of a low index region with index $n_{slot}$ sandwiched between two high index slabs with index $n_{slab}$, the eigenmodes of the system may be solved using coupled mode theory to find the interaction between
the strongly coupled fundamental eigenmodes modes of the two individual high index slab waveguides. The resulting eigenmode is given as a superposition of the two individual slab eigenmodes:

\[ \psi_{\text{gap}} = a\psi_{\text{slab}1} + b\psi_{\text{slab}2} \]  

(2.1)

Where \( a \) and \( b \) are the amplitudes of the fundamental basis modes of each slab waveguide.

In the case of two slabs of infinite height and finite width, \( W \), the transverse electric field of the gap mode \( E_x \) can be calculated explicitly:

\[
E_x = A \begin{cases} 
\frac{1}{n_s^2} \cosh(\gamma_s x) & |x| < a \\
\frac{1}{n_H^2} \cosh(\gamma_s a) \cos[\kappa_H(|x| - a)] + \frac{\gamma_s}{n_s^2 \kappa_H} \sinh[\kappa(|x| - a)] & a < |x| < b \\
\frac{1}{n_C^2} \left( \cosh(\gamma_s a) \cos[\kappa_H(b - a)] + \frac{n_H^2 \gamma_s}{n_s^2 \kappa_H} \sinh(\gamma_s a) \sin[\kappa_H(b - a)] \right) e^{-\gamma_C(|x| - b)} & |x| > b 
\end{cases}
\]  

(2.2)

where \( \kappa_H \) is the transverse wave number in the high-index slabs, \( \gamma_C \) is the field decay coefficient in the cladding, \( \gamma_s \) is the field decay coefficient in the slot and constant \( A \) is given by:

\[ A = A_0 \sqrt{\frac{k_0^2 n_H^2 - \kappa_H^2}{k_0}} \]  

(2.3)

where \( A_0 \) is an arbitrary constant and \( k_0 = 2\pi/\lambda_0 \) is the vacuum wavenumber. The transverse parameters, \( \kappa_H, \gamma_s \) and \( \gamma_C \) simultaneously obey the relations \( k_0^2 n_H^2 - \kappa_H^2 = k_0^2 n_C^2 + \gamma_C^2 = k_0^2 n_s^2 + \gamma_s^2 = \beta^2 \), where \( \beta \) is the eigenmode propagation constant which can be found by solving the transcendental characteristic equation:

\[ \tan[\kappa_H(b - a) - \Phi] = \frac{\gamma_s n_H^2}{\kappa_H n_s^2} \tanh(\gamma_s a) \]  

(2.4)

where \( \Phi = \arctan[\gamma_C n_H^2/(\kappa_H n_C^2)] \) [30].

In the case of non-infinite height slab waveguides, the eigenmodes are most easily computed numerically with a tool such as COMSOL multiphysics. The results of one such
Figure 2.1: This figure shows the geometry of a slot waveguide with (a) infinite height and (b) finite height.
computation are shown in figure 2.2 where two 160nm wide by 220nm tall silicon ridges are separated by a 130nm gap to form a coupled gap waveguide mode. The mode concentrates approximately 60% of the optical power into the slot between the ridges. Changing the physical or optical parameters of the system can alter the amount of power carried in the gap mode and multiple gap waveguides have been shown to provide the highest concentration of optical field in the low index region [31].

Figure 2.2: This figure shows the fundamental TE mode of a gap waveguide that is composed of two silicon ridges 220nm tall, 160nm wide and separated by a 130nm gap along with a cross section of the transverse E-field of that mode.

One of the most interesting properties of gap waveguides is that most of the optical field is carried outside of the silicon. This is particularly useful for constructing active devices such as modulators and switches because silicon is a poor material for active optical devices due to its zero linear electro-optic coefficient and indirect band gap. Redirecting power from the silicon waveguide into the gap in a gap waveguide opens up the possibility to include any number of interesting materials in the the construction of gap waveguide photonic devices. Some of the most promising materials for integration into silicon photonic devices are electro-optic polymers. By filling the gap with an electro-optic polymer, the optical properties of the
device may be tuned by applying an electric field to the device. The following two sections present two such devices - a Mach Zehnder Interferometer using gap waveguides filled with an electro-optic polymer and a gap waveguide directional coupler switch.

2.2 Gap Waveguide Devices

2.2.1 Mach Zehnder Interferometer Modulator

A Mach Zehnder Interferometer (MZI) is a device that takes an input optical signal, splits it equally along two paths and then recombines the signals to create an interference effect. The two optical signals accumulate phase at varying rates while traversing the arms of the Mach Zehnder interferometer and when they are merged, they interfere either constructively or destructively according to their relative phases. In the case of guided wave optics we can assume that the optical fields only vary along the direction of propagation inside the waveguide (i.e. they are eigenmodes of the waveguides) and are give by

\[ E_1(L_1) = \frac{1}{2} E_0 e^{-i\beta_1 L_1} \]
\[ E_2(L_2) = \frac{1}{2} E_0 e^{-i\beta_2 L_2} \]

where \( L_1 \) and \( L_2 \) are the lengths of the two arms of the MZI.

\[ E_{\text{out}} = E_1(L_1) + E_2(L_2) = \frac{1}{2} E_0 (e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2}) \]  \hspace{1cm} (2.5)

where \( \beta = \frac{2\pi n_{\epsilon f} L}{\lambda_0} \) is the propagation constant of the mode in each arm. If we solve for the intensity output from the MZI, we find:

\[ I_{\text{out}} = |E_{\text{out}}||E_{\text{out}}^*| = \frac{1}{4} I_0 (\cos^2(\beta_1 L_1) + \cos^2(\beta_2 L_2)) \]  \hspace{1cm} (2.6)

There are two special cases to this solution. If \( \beta_1 L_1 = \beta_2 L_2 + 2n\pi \) where \( n \) is an integer, then equation 2.6 becomes:

\[ I_{\text{out}} = |E_{\text{out}}||E_{\text{out}}^*| = \frac{1}{2} E_0 (2 \cos(\beta_1 L_1) + i \sin(\beta_1 L_1))^2 = I_0 \]  \hspace{1cm} (2.7)

And if \( \beta_1 L_1 = \beta_2 L_2 + n\pi \) then:

\[ I_{\text{out}} = |E_{\text{out}}||E_{\text{out}}^*| = \frac{1}{2} E_0(0)^2 = 0 \]  \hspace{1cm} (2.8)
These are the conditions of perfect constructive and destructive interference between two optical waves and form the basis for creating an electro-optic phase modulator.

The basic premise is to create an MZI structure with two identical arms so that in the “on” state (i.e. no applied voltage), the signals from the two arms recombine constructively and a signal is transmitted at the other end of the device. However, by applying a voltage to one or both arms of the MZI, the propagation constants of the optical signals in those arms are changed such they they accrue phase at different rates. After traversing each arm, the two signals have accumulated a phase difference of $\pi$ which causes them to interfere destructively when recombined and blocks the transmission of the device. Through this process, an optical signal can be amplitude modulated such that in the “on” it transmits light and in the “off” state it does not.

Such a device has been designed using gap waveguides infiltrated with an electro-optic polymer that changes its refractive index in proportion to the voltage applied to it. The device is shown in figures 2.6 and 2.7. It is made of a 50/50 power splitter to divide the optical power evenly between each arm, a strip-to-slot coupler at each to convert the ridge waveguide mode into a gap waveguide mode and then back to a ridge mode and a pair of 200 $\mu$m gap waveguides that serve as the two arms of the MZI. The optical mode of the gap waveguides is shown in figure 2.3. In order to evaluate the performance of the device, the electrostatic response of the system to a voltage applied to electrodes on either side of the arm was evaluated. The results of this simulation can be seen in figure 2.4. Finally, the transmission of the device is calculated versus applied voltage assuming an EO coefficient of the polymer of 10 pm/V. The total voltage necessary to cause modulation is 2000V, far too high to be usable in an integrated circuit. Higher EO coefficient polymers exist, such as molecular glasses based on the reversible self-assembly of aromatic/perfluoroaromatic dendron-substituted nonlinear optical chromophores [32] which can have EO coefficients as high as 200 pm/V. However, this only reduces the necessary voltage from 2000V to 100V, which is still far too large. In order to reduce the applied voltage, the device must be made
longer to allow more time for phase to accumulate in the arms. In order to reduce the modulation voltage to ± 1V, the arms must be lengthened from 200 µm to 20 mm which is unacceptably long. This demonstrates that gap waveguides are potentially useful devices for creating active photonic devices, but they have a number of limitations - most notably their insensitivity to small changes in the index of the gap and electrical inaccessibility.

After the disappointing performance of gap waveguide MZI modulators, we will examine a gap waveguide optical switch to see if it can demonstrate adequate performance.

2.2.2 Gap Waveguide Directional Coupler Switch

We propose an electro-optic switch based on gap waveguides where the coupling between two strongly coupled gap waveguides is tuned via an applied electric field. The schematic for the device is shown in figure 2.8. The basic theory governing the operation of this device is described in detail in chapter 4, but briefly, when two waveguides are placed in close proximity to one another, the symmetry that create the eigenmodes of each waveguide is broken and a new system with a different set of eigenmodes is created. This new system allows power to couple from one waveguide to another and for the case of symmetric waveguides can be described by the following equation:

\[ a(z, t) = B_0 \frac{\kappa_{ab}}{\kappa} e^{i(\omega_\alpha t - \beta_\alpha)} \sin(\kappa z) \]  \hspace{1cm} (2.9)

\[ b(z, t) = B_0 e^{i(\omega_\beta t - \beta_\beta)} \cos(\kappa z) \]  \hspace{1cm} (2.10)

where \( \kappa^2 = \kappa_{ab}\kappa_{ba} \). The distance required to couple power completely from one waveguide to the other is called the coupling length and is given by:

\[ L_c = \frac{\pi}{\beta_{sym} - \beta_{asym}} \]  \hspace{1cm} (2.11)

where \( \beta_{sym} \) is the propagation constant of the symmetric mode of the coupled system and \( \beta_{asym} \) is the propagation constant of the antisymmetric mode. Larger differences between the two propagation constants create shorter coupling lengths.
Figure 2.3: This figure shows the optical gap mode of each of the unperturbed MZI modulator arm.
Figure 2.4: This figure shows an electrostatic simulation of the gap waveguides used in each arm of the MZI modulator. The left electrode is held at +1V and the right electrode is held at −1V. The voltage drop across the gap is 0.4V.
Figure 2.5: This figure shows the transmission of the gap waveguide MZI as a function of applied voltage. This assumes a polymer with an EO coefficient of 10 pm/V and electrodes placed 1 \( \mu \text{m} \) to each side of each arm of the MZI.

Figure 2.6: This figure shows a COMSOL simulation showing the transmission of the gap waveguide MZI in the block state. The light on the top arm is in phase with the light in the bottom arm and adds constructively to the light in the bottom arm.
Figure 2.7: This figure shows a COMSOL simulation showing the transmission of the gap waveguide MZI in the block state. The light on the top arm is $\pi$ out of phase with the light in the bottom arm and scatters out of the waveguide when they try to recombine.
These coupled waveguides can be used to create a switch if the coupling between them can be altered in some way. Here we propose to alter the coupling between two gap waveguides using an applied voltage to change the index of an electro-optic polymer infiltrated into the gaps. In order to evaluate the performance of the device, an electrostatic simulation was carried out in COMSOL to find the response of the system to a voltage applied to the two bottom electrodes (see figure 2.9). By applying a voltage to the device, the refractive index of the polymers inside the gap is changed, altering the coupling characteristics of the switch. This can cause power to transfer from one output arm of the device to the other as seen in figure 2.10. However, as with the previous device, the change in refractive index necessary to cause switching is quite high ($\Delta n = 0.29$) which requires an applied voltage of well over 1000 volts for a 200 µm long switch. Again, this device suffers from lack of electrical accessibility and a low sensitivity to refractive index changes of the gap material. In order to develop usable active photonic devices, we must find a structure that increases the sensitivity of the system to refractive index perturbations and allows more direct electrical access to the electro-optic materials. Fortunately, hybrid waveguides consisting of a high index slab, a low index gap and a metallic cap were recently discovered [33] and show great promise for addressing the problems that plague gap waveguide active devices.
**Push-Pull EO Modulator**

Figure 2.8: This figure shows the basic design of a push-pull gap waveguide directional coupler switch. The silicon ridges are 160nm wide by 220nm tall and the gap between them is 130nm. The anode and cathode are 1 $\mu$m to each side of the center ridge and the top electrode is 1 $\mu$m above the oxide substrate.
Figure 2.9: This figure shows and electrostatic simulation of the gap waveguide three ridge switch. The total voltage applied that aligns with the optical polarization is fairly low, only 0.1V for $\pm$ 1V applied to the electrodes. However, the applied electric fields are in opposite directions which creates a push-pull scenario that effectively doubles the efficiency of the system.
Figure 2.10: This figure shows a COMSOL simulation showing the transmission of the gap waveguide three ridge switch in various states. (a) shows the transmission of the switch in the bar state (b) shows the transmission of the switch in the cross state and (c) shows the transmission of the switch working as a 50/50 power splitter.
3.1 The Fundamentals of Hybrid Waveguides

High index contrast waveguides are promising components for the on-chip highly integrated photonic networks which are the current forerunners in the race towards more powerful computer systems. Integrated optics can confine, guide, filter, bend and split light at a very small scale, though they are still limited by diffraction. The lower limit for the size of optical waveguides is approximately one half the wavelength of the light carried by the guide. The diffraction limit on the size of photonic devices is one of the factors that limits their use in highly integrated circuits. Plasmonic waveguides have the ability to confine light much more strongly than dielectric waveguides, but the use of surface plasmon polaritons for propagating light introduces a large amount of propagation losses into the system. There is a fundamental tradeoff between mode confinement and propagation loss, however, a hybrid system composed of both metallic and a dielectric waveguides may offer many of the benefits of each system while mitigating some of their problems.

Hybrid waveguides are a variation on horizontal gap waveguides [31], where the top part of the silicon waveguide is replaced with a thin layer of metal. The main feature of this kind of design is a thin low index spacer layer sandwiched between a high index ridge and a metal substrate or cap. In this kind of structure, the main part of the mode energy is squeezed into the thin low index layer, and thus we can get a deep sub-wavelength optical mode while mitigating the propagation losses from the metal. Other configurations of hybrid
waveguides are also possible such as a dielectric cylinder suspended above a metallic plane [34] or a thin metal layer wrapped around a silicon ridge with a dielectric spacer [23] [50]. These designs, while interesting, pose difficult problems with regard to fabrication and integration into the CMOS process that is the mainstay of the semiconductor industry. Instead, we propose a simplified design based on pre-processed silicon photonic circuits that can be post-processed into hybrid waveguides using relatively simple materials and processes. Simplified fabrication also reduces the likelihood of fabrication errors which can alter the performance of the devices. The proposed hybrid waveguide design is a silicon ridge, immersed in a dielectric "cladding" which then has metal deposited on top. This forms a thin layer of dielectric material between the top surface of the silicon ridge and the metal cap wherein most of the optical power is carried. The primary benefits of hybrid waveguides are sub-diffraction light confinement, inverted wave guidance where the light is confined to a low index region surrounded by higher index materials and direct electrical access to the guiding region.

In all of the following analysis, gold will be used as the metal layer, and its optical properties will be estimated using a Lorentz-Drude model [35] – though other metals could also be used to design hybrid waveguides and devices.

The basic principle that allows hybrid waveguides to achieve sub-diffraction light confinement and inverted wave guidance is that at a high index contrast interface, Maxwell’s equations state that, to satisfy the continuity of the normal component of electric flux density D, the corresponding electric field (E-field) must undergo a large discontinuity with much higher amplitude in the low-index side [51]. This effect can be used to strongly enhance the field inside a nanometric gap between two high index structures, such as a silicon ridge and a metal film. Hybrid waveguides operate by superimposing the discontinuous E-fields of the two sides of the waveguide at the low to high index interfaces of the structure. The E-field that results from the superposition of these two modes (see Figure 3.1), becomes the lowest energy mode of resulting system. Additionally, we find that this mode must have its E-field
Figure 3.1: (a) TM surface mode of just the gold film. (b) TM mode of just the silicon ridge. (c) TM mode of the combined system. (d) Vertical component of the E-field along a vertical cross section of the sum of the modes in (a) and (b) superimposed with the vertical component of the E-field of the combined system. The shape of the mode is the same in each case, leading to the conclusion that the mode in (c) is a combination of the modes in (a) and (b).
perpendicular to the two interfaces that contribute to its formation.

Coupled mode theory can be used to describe the hybrid mode since, to first order, it is created from the interaction of two strongly coupled modes - the silicon ridge waveguide mode and the surface mode of the metallic cap. The hybrid mode can be described using a two dimensional matrix approach wherein two basis vectors representing the fundamental TM mode of the silicon ridge and the surface mode of the metal plane are super-imposed to create two possible hybrid modes, denoted $\psi_+$ and $\psi_-$.

$$
\psi_{\pm}(W, G) = a_{\pm}(W, G)\psi_{wg}(W) + b_{\pm}(W, G)\psi_{metal}
$$

(3.1)

where $a_{\pm}$ and $b_{\pm}$ are the amplitudes of the silicon ridge waveguide and the metal surface basis modes respectively. The modes can be represented by their effective indices and those can be parameterized with respect to the width of the silicon ridge (assuming constant height), $W$, and the gap between the top of the silicon and the metal cap, $G$. The modes of the coupled system are characterized by the following system of equations:

$$
\begin{pmatrix}
    n_{wg}(W) & V(W, G) \\
    V(W, G) & n_{metal}
\end{pmatrix}
\begin{pmatrix}
    a_{\pm}(W, G) \\
    \sqrt{1 - |a_{\pm}(W, G)|^2}
\end{pmatrix}
= n_{\pm}(x, y)
\begin{pmatrix}
    a_{\pm}(W, G) \\
    \sqrt{1 - |a_{\pm}(W, G)|^2}
\end{pmatrix}
$$

(3.2)

where $V(W,G)$ is the coupling strength between the silicon ridge and metal surface modes and mode amplitude normalization implies $b_{\pm}(W, G) = \sqrt{1 - |a_{\pm}(W, G)|^2}$. The solutions to the characteristic equation of the coupled mode theory are $n_{\pm} = \bar{n}(W, G) \pm \Delta(W, G)$, where $\bar{n} = (n_{wg} + n_{metal})/2$ and $\Delta^2(W, G) = (n_{wg} - n_{metal})^2/4 + V^2(W, G)$. The mode amplitude $|a_{+}(W, G)|^2$ provides a measure of how dielectric or metallic the hybrid waveguide mode is, and is given by:

$$
|a_{+}(W, G)|^2 = \frac{V^2(W, G)}{(n_{+}(W, G) - n_{wg}(W))^2 + V^2(W, G)}
$$

(3.3)

Which can be rewritten as:
\[
|a_+(W,G)|^2 = \frac{n_{hyb}(W,G) - n_{metal}}{(n_{hyb}(W,G) - n_{wg}(W) + (n_{hyb}(W,G) - n_{metal}))}
\] (3.4)

Where \(n_{hyb} = n_+\) [34]. Figure 3.2 shows how the mode amplitude \(|a_+(W,G)|^2\) varies with the gap between the silicon ridge and metal cap for different waveguide widths.

The combination of these two modes creates a novel waveguide where a large portion of the power is carried in the gap between the metal and the silicon. In addition, there are no fundamental limitations on the size of the spacer layer. Since the mode is created by superimposing E-fields which are discontinuous at a boundary and decaying exponentially in space, the standard restrictions governing guided modes do not apply. Instead, the overlap between the two fields only increases as the gap between the silicon and metal is decreased, leading to even larger field enhancement in the spacer layer (see figure 3.3(a)). Not only does decreasing the spacer layer concentrate the field in the vertical direction, but somewhat counter-intuitively, in the transverse direction as well (see figure 3.3(b)). This is a result of the metal film interrupting the transverse expansion of the TM mode of the silicon ridge (refer back to figure 3.1(b)).

The dispersion characteristics of the hybrid waveguide have also been calculated using COMSOL for a variety of spacer layer thicknesses (see figure 3.4). The choice of spacer layer thickness determines how metallic the hybrid waveguide behaves. For very small gaps, the waveguide is quite metallic - characterized by high loss and high dispersion. For large gaps, the waveguide is much more dielectric in nature with lower loss and less dispersion. This underlines a fundamental tradeoff present in hybrid waveguides, namely field confinement and enhancement vs. loss. This tradeoff allows one to design hybrid waveguides for a number of purposes since their optical properties are highly dependent on their geometry.

Hybrid waveguides are a novel and flexible new form of waveguide with many different potential applications. Two such application which will receive further treatment in this dissertation are directional couplers and electro-optical switches.
Figure 3.2: (This figure shows how the mode amplitude $|a_+(W,G)|^2$ varies with the gap between the silicon ridge and the metal cap, $G$, for different waveguide widths, $W$. This particular configuration for a hybrid waveguide retains its dielectric properties throughout the full range of possible gaps and never becomes plasmonic in nature ($|a_+(W,G)|^2 < 0.5$).
Figure 3.3: (a) Field enhancement of the E-field in the spacer layer as the thickness of the layer is decreased. (b) As the thickness of the spacer layer is decreased, the transverse extent of the E-field also decreases.

Figure 3.4: (a) The change in effective index of the hybrid waveguide vs. wavelength is shown for a variety of spacer layer thicknesses. As the thickness of the spacer layer decreases, the waveguide becomes more dispersive as the optical properties of the metal film begin to dominate its behavior. (b) The propagation length (the distance into which the field decays to 1/e of its starting value) of the hybrid waveguide is highly dependent on the thickness of the spacer layer. Small gap sizes produce more lossy waveguides.
3.2 Hybrid Waveguide Devices

3.2.1 Directional Couplers

Optical directional couplers are passive optical devices that couple light from one waveguide to another. They are very useful optical devices that can be used as arbitrary power splitters [36], polarization filters [37], wavelength filters [38] and optical switches [39]. The behavior of optical directional couplers is governed by optical coupled mode theory as detailed by J.R. Pierce in 1954 [47] and codified for optical waveguides by Amnon Yariv in 1973 [48].

The propagation and interaction of optical fields inside dielectric waveguides is governed by coupled-mode theory. There exists a formalism for arbitrary waveguides, but for the purposes of this document, this section will focus on describing the behavior of two symmetric coupled waveguides. Symmetric waveguides are automatically phase matched, which dramatically simplifies the mathematics involved in describing the behavior of these structures.

In a single waveguide, there exists a finite set of eigenmode solutions to Maxwell’s equations that satisfy the guided wave conditions. In a single mode waveguide, there exists only a single solution to these equations which fully characterizes the propagation behavior of light through that waveguide. The introduction of a second waveguide breaks the symmetry that produced the original eigenmode solution to Maxwell’s equations and creates a new system with a different set of eigenmodes. The new system obeys the following set of coupled differential equations:

\[
\frac{dA}{dz} = \kappa_{ab} B e^{-i\Delta z} \tag{3.5}
\]

\[
\frac{dB}{dz} = \kappa_{ba} A e^{+i\Delta z} \tag{3.6}
\]

where the phase-mismatch constant \(\Delta\) depends on the propagation constants of \(\beta_a\) and \(\beta_b\). The coupling coefficients \(\kappa_{ab}\) and \(\kappa_{ba}\) are determined by the geometry and optical properties
of the coupled system and will be determined using COMSOL's eigenmode solver. For a symmetric, lowest order set of coupled waveguides, the coupling coefficients \( \kappa_{ab} \) and \( \kappa_{ba} \) are complex conjugates of one another. This condition allows the power exchange between the two waveguides may be solved analytically [48]:

\[
a(z, t) = B_0 \frac{\kappa_{ab}}{\kappa} e^{i(\omega_a t - \beta_a)} \sin(\kappa z) \\
b(z, t) = B_0 e^{i(\omega_b t - \beta_b)} \cos(\kappa z)
\]

(3.7)

(3.8)

where \( \kappa^2 = \kappa_{ab} \kappa_{ba} \). The distance required to couple power completely from one waveguide to the other is called the coupling length and is given by:

\[
L_c = \frac{\pi}{\beta_{sym} - \beta_{asym}}
\]

(3.9)

where \( \beta_{sym} \) is the propagation constant of the symmetric mode of the coupled system and \( \beta_{asym} \) is the propagation constant of the antisymmetric mode. Larger differences between the two propagation constants create shorter coupling lengths.

### 3.2.2 Optical Switches

Directional couplers can be used to create switches if some mechanism for changing the coupling length of the optical modes is introduced. Common methods for changing the coupling length are the thermoptic effect [40], charge injection [42] [41], the electro-optic effect [43] [44] [45], \( \chi^3 \) non-linearity or mechanical tuning. Regardless of the method for altering the optical parameters of the directional coupler, the basic operation remains the same. In one state - call it the Bar state - light couples from one waveguide to the other and back again some number, \( N \), times and eventually is output into the bar arm of the directional coupler (see figure 3.6). When the coupling length is changed, the light no longer is fully coupled to the bar state at the output and instead has some portion of its power coupled into the cross state. For an effective switch, the change in coupling length results in all of the power being coupled to either the bar or the cross state at the output of the directional coupler.
Figure 3.5: This figure shows a COMSOL simulation illustrating the way that power couples between two symmetric dielectric waveguides. This shows a top down view of the power carried in each waveguide after it is injected into the directional coupler.

Figure 3.6: This figure shows the difference between the bar and cross states of a directional coupler.
In order to describe the operation of an optical switch, we must first represent the system mathematically. Symmetric coupled waveguides exchange optical power in a sinusoidal fashion. If power is input onto only one arm of the directional coupler, the optical power by each waveguide can be represented as follows:

\[ P_{\text{bar}} = P_o \cos^2 \left( \frac{\pi}{L_c} z \right) \]  

\[ P_{\text{cross}} = P_o \sin^2 \left( \frac{\pi}{L_c} z \right) \]  

where \( P_{\text{bar}} \) is the power carried in the bar waveguide, \( P_{\text{cross}} \) is the power carried in the cross waveguide, \( P_o \) is the power input to the directional coupler, \( L_c \) is the coupling length of the directional coupler and \( z \) is the distance along the directional coupler. From this formulation, we can also express the power carried in each waveguide after the coupling length has been modified as described previously. The only thing that changes is the coupling length, so to differentiate the two states of the switch we will refer to the coupling length in the first state as \( L_{c1} \) and the coupling length in the second state as \( L_{c2} \). For simplicity, we will assume that \( L_{c1} < L_{c2} \).

\[ P_{1\text{bar}} = P_o \cos^2 \left( \frac{\pi}{L_{c1}} z \right) \]  

\[ P_{1\text{cross}} = P_o \sin^2 \left( \frac{\pi}{L_{c1}} z \right) \]  

\[ P_{2\text{bar}} = P_o \cos^2 \left( \frac{\pi}{L_{c2}} z \right) \]  

\[ P_{2\text{cross}} = P_o \sin^2 \left( \frac{\pi}{L_{c2}} z \right) \]  

In order to find the length necessary to switch from the bar state to the cross state given \( L_{c1} \) and \( L_{c2} \), we must find a relationship that links these equations together. Let us begin our analysis with the bar states of the modified and unmodified directional couplers.

In the unmodified directional coupler, light enters the device through one input arm, couples back and forth some number of times and emerges from the device on the same
arm. The output of the bar state is therefore equal to \( P_o \) (assuming a lossless device) and the output of the cross state is 0. Substituting this solution into the equation for \( P^1_{\text{bar}} \) and \( P^1_{\text{cross}} \) we find that \( \frac{\pi}{L_{c1}} z = N \pi \) where \( N \) is an integer that describes the number of times the power transferred from one waveguide to the other. In order to be an effective switch, when the system is modified to change \( L_{c1} \) to \( L_{c2} \), the new output of the bar state is 0 and the output of the cross state is \( P_o \). In order to minimize the length of the switch, this should occur after \( \frac{2N-1}{2} \) power transfers between waveguides. This condition leads to the following relationship: \( \frac{\pi}{L_{c2}} z = \frac{2N-1}{2} \pi \). These two equations can be solved for \( z \) and set equal to one another.

\[
NL_{c1} = \frac{2N - 1}{2} L_{c2} \quad (3.16)
\]
\[
N = \frac{L_{c2}}{2(L_{c2} - L_{c1})} \quad (3.17)
\]
\[
Z = \frac{L_{c1} L_{c2}}{2(L_{c1} - L_{c2})} \quad (3.18)
\]

\( Z \) is the minimum length of a switch based on a directional coupler that can be modified to have coupling lengths \( L_{c1} \) or \( L_{c2} \). The switching process is illustrated in figure 3.7.

The directional coupler switch forms the design basis for the integrated optical switch discussed in later sections of this work. The relative simplicity of the design, non-resonant behavior and design flexibility make it an excellent platform for the design of highly efficient and compact optical devices.

### 3.2.3 Hybrid Waveguide Directional Couplers

As with standard waveguides, when two hybrid waveguides are brought into close proximity, they experience power coupling. The introduction of a second hybrid waveguide breaks the symmetry that produced the original eigenmode solution to Maxwell's equations and creates a new system with a different set of eigenmodes.
Figure 3.7: This figure gives a simple demonstration of how a directional coupler switch works. The solid line represents the power carried in the unmodified bar mode for a directional coupler with $L_{c1} = 5\mu m$. The dashed line represents the power carried in the modified bar mode with $L_{c2} = 4\mu m$. The total length of the device must be 10\mu m to enable proper switching with these parameters.
Compared to silicon ridge directional couplers ([46] and [19]), hybrid waveguides have coupling lengths that are significantly shorter, especially for larger waveguide separations (see figure 3.8). The main cause for the difference in coupling lengths is that silicon ridge waveguides create a very constrained optical system. The optical mode carried in the silicon is tightly confined by the edges of the ridge. This limits the amount that the mode can move and reshape itself inside the confining silicon. In contrast, the hybrid waveguide’s optical mode is laterally unbounded due to being composed partly of a distributed metal surface mode. This mode extends uniformly along the metal cap and does not decay exponentially in the transverse direction like the guided modes do. This gives the hybrid waveguides a much longer "reach" than traditional waveguides. The influence of the laterally confined waveguide mode serves to tether the optical field to the silicon ridge and limit its transverse extent. Tuning the $|a_+(W,G)|^2$ parameter mentioned in section 4.1.1 allows for another degree of freedom in determining the coupling parameters of the hybrid waveguide system besides the center to center separation of the waveguides. Additionally, the relaxed transverse confinement of the hybrid waveguide modes allows the mode to slide around the surface of the waveguide when it is perturbed. This added freedom allows the symmetric and anti-symmetric modes of the hybrid waveguide system to have larger differences than ridge waveguides which in turn leads to shorter coupling lengths. In addition, the lower constraints on the optical mode of the hybrid waveguide makes them much more sensitive to perturbations. This extra sensitivity leads to a much higher degree of tunability in the optical properties of the hybrid waveguide which makes them a promising platform for the development of active devices such as switches and modulators [52].

The dependance of the coupling length of the directional coupler on the center to center spacing of the hybrid waveguides is shown in figure 3.8. Larger differences between the two propagation constants create shorter coupling lengths. As is shown, wider silicon ridges and smaller center to center separations produce the largest differences in propagation constants and hence the shortest coupling lengths. This property is highly desirable for the
Figure 3.8: This figure shows the relationship between coupling length and center to center spacing for two hybrid waveguide geometries and a 450nm by 220nm silicon ridge waveguide. The hybrid waveguide with narrow ridges has a cutoff at around a gap of 300nm and therefore, never achieves the small coupling lengths that wider silicon ridges achieve for small gaps. The ridge waveguide always has a larger coupling length than its hybrid counterparts due to stronger confinement of the optical mode.
design of active devices. The mechanism underlying the very short coupling lengths in hybrid waveguides is the interaction of the magnetic fields of the two modes. This effect is illustrated in figure 3.9. In the symmetric mode, the magnetic fields of the two modes have the same sign and create an overlapping mode. This tends to cause the entire mode to bend inward. In the odd mode of the coupled structure, the magnetic fields have opposite signs and tend to repel each other. This causes the modes to bend outward away from each other. The net result of this interaction is a very large mode mismatch between the symmetric and antisymmetric modes of the device, even for relatively large spacings between the silicon ridges.

3.2.4 Electro-Optical Switches Based on Hybrid Waveguides

The short coupling lengths of hybrid waveguide directional couplers makes them a promising platform for constructing active optical devices. Optical switches are important components for future photonic networks. Not only can they control data flow, but if they can operate at sufficient speeds, they can also serve as modulators. One of the main problems facing high density integration of photonic networks is that most optical switches are quite large and consequently slow. However, hybrid waveguides provide an opportunity to create an extremely compact electro-optic switch that is compatible with standard CMOS and VLSI processes. Both electrorefractive [53] and electroabsorptive [54] devices have been demonstrated using active electrical control of integrated plasmonic–dielectric structures. In the following section we propose a design for an electro-optical switch based on electrorefractive polymers integrated with a hybrid waveguide directional coupler.

A schematic of the proposed EO switch can be seen in Figure 3.13. The device is the product of a detailed optimization process. The primary goal of the optimization was to minimize the switching length for an electro-optical switch composed of two coupled hybrid waveguides with a secondary constraint that the propagation length of the design had to be longer than the length of the switch. The optimization was performed in three stages: a
Figure 3.9: This figure shows how the magnetic components of the optical modes in a hybrid waveguide contribute to the behavior of the directional coupler. The hybrid waveguides used in this simulation are 220nm tall 300nm wide and have a 50 nm gap. All the images are the results of a COMSOL eigenmode simulation and the color field shows the TM E-Field of the mode and the contour plot shows the transverse B-Field. (a) The symmetric mode of two hybrid waveguides separated by 1 µm. (b) The antisymmetric mode of two hybrid waveguides separated by 1 µm. In both of these modes, the magnetic fields interact quite weakly, resulting in very little mode distortion. (c) The symmetric mode of two hybrid waveguides separated by 400 nm. (d) The antisymmetric mode of two hybrid waveguides separated by 400 nm. In both of these modes, the magnetic fields interact strongly, resulting in a large distortion of the mode and contributing to a much higher than normal mode mismatch between the symmetric and antisymmetric modes.
Figure 3.10: This figure shows the relationship between the even and odd modes of the coupled hybrid waveguides and the center to center spacing of the waveguides. Two different waveguides are shown, 100 nm wide silicon ridges and 300 nm wide silicon ridges. Both systems have a 100nm spacer layer. The narrower waveguides have a mode cutoff on the odd mode for spacing below 300 nm. Also shown are the modes of a 450 nm by 220 nm silicon ridge waveguide for comparison.
Figure 3.11: This figure shows a COMSOL simulation of two coupled hybrid waveguides as well as a cross section of the TM E-Field taken through the center of the spacer layer for a 100 nm gap. The mismatch between the symmetric and antisymmetric mode is fairly large, which leads to strong coupling between the two waveguides.
Figure 3.12: (a, b) A COMSOL simulation showing the E-field (surface plot) and B-field (contour plot) of the even and odd modes of a coupled hybrid waveguide system. The opposite sign of the B-fields in the odd mode causes the modes to repel each other. This leads to the modes ”bending” away from the center of the device. In the even mode, the B-fields have the same sign which causes them to merge together. This in turn causes the overall mode to ”bend” inward towards the center of the coupler. Taken together, this bending creates a device with shorter coupling lengths than normal ridge waveguides and also produces a more dynamic and tunable system. (c, d) A COMSOL simulation showing the E-field (surface plot) and B-field (contour plot) of the even and odd modes of a coupled ridge waveguide system for comparison. The high isolation of the modes due to the strong confinement of the silicon inhibits mode mobility and prevents the kinds of coupling demonstrated in hybrid systems.
very coarse optimization covering a large portion of the design space to identify promising geometries, a secondary optimization around any promising results from the coarse search of the design space to determine the viability of that design and finally a fine optimization on the best design from the previous optimizations to find the optimum parameters for the hybrid waveguide switch. The optimization parameters were the width of the silicon ridges, the center to center spacing of the two ridges and the gap between the tops of the ridges and the metal cap. This procedure yielded an optimum design which is described in detail below.

The device sits on an oxide substrate and is composed of silicon ridges doped with phosphorus to a concentration of \(10^{18} \text{cm}^{-3}\) to aid the electrical operation of the device \((n_{\text{si}} = 3.44 + 0.007i)\) with height, \(H_{\text{si}}\), 220 nm and width, \(W_{\text{si}}\), 300 nm. The ridges have a center to center separation of 400 nm. Two gold electrodes are deposited in close proximity to the silicon ridges. These electrodes are 50nm thick and are modeled as touching the edges of the silicon ridges. However, a 50nm layer of doped silicon is left underneath the ridges to ensure electrical contact between the bottom electrodes and the silicon ridges. The silicon ridges are immersed in a polymer layer with index, \(n_{\text{poly}}\), equal to 1.7. The polymer layer is 270nm thick. This creates a 50nm spacer layer between the silicon and metal. The top layer is a gold film whose permittivity is given by the Drude model [35]. The metal film is 100nm thick and serves as the top electrode for the system. For the sake of this analysis, the top metal electrode is assumed to have an area of 15\(\mu\text{m}\) x 2\(\mu\text{m}\) and the bottom electrodes are designed to have minimal overlap with the top electrode to minimize the capacitance of the device.

Mode analysis in COMSOL finds that the coupling length of this structure is 2.6 \(\mu\text{m}\) for a polymer index of 1.69 and 2.7 \(\mu\text{m}\) for a polymer index of 1.71. This change in index can be achieved with a drive voltage of ± 1V using a polymer with an Pockel’s coefficient of 200 pm/V such as molecular glasses based on the reversible self-assembly of aromatic/perfluoroaromatic dendron-substituted nonlinear optical chromophores [32]. For a
Figure 3.13: Cross sectional view of the EO switch.
switching length given by $L = L_{c1}L_{c2}/(2(L_{c1} - L_{c2})$ the total device length is found to be $15 \mu\text{m}$. The propagation length of this device is also found from the mode analysis and is given by $L_p = \frac{\lambda}{2\pi n''_{eff}}$ where $\lambda$ is 1550 nm and $n''_{eff}$ is the imaginary part of the effective index. The propagation length is found to be $40 \mu\text{m}$, which leads to a propagation loss along the length of the device of 1.6 dB. In order to determine the extinction ratio of the device, a mode propagator was used to find the evolution of the optical signal carried on each arm of the directional coupler with distance propagated. After the input field was propagated one coupling length, or $2.7 \mu\text{m}$, the extinction ratio was calculated by integrating the power on each arm of the directional coupler and taking the ratio of those powers (see figure 3.14). The extinction ratio was found to be 29.5 dB.

The modulation performance of the device depends on the uniformity of the voltage applied to the electro-optic polymer and the overlap of that field with the optical field. Electrostatic simulations in COMSOL show that the overlap integral of the optical field with the applied electric-field that drives the electro-optic effect in the polymer is 81% of a completely uniform field and 70% of the optical field is subjected to a fully uniform voltage field (see figure 3.15).

Due to the very fast response of EO polymer (on the order of femtoseconds), the speed of the device is only limited by its electrical characteristics. To this end, the device can be approximated as a set of parallel plate capacitors whose capacitance is given by $C = \varepsilon_r\varepsilon_0\frac{A}{d}$, where $\varepsilon_r$ is the permittivity of the polymer, $A$ is the area of the electrodes and $d$ is the separation between electrodes. Electrostatic modeling in COMSOL has shown that the doped silicon ridges have negligible field penetration from the applied voltage and have a very uniform electric field (see figure 3.15) and thus can be well approximated as the bottom plates of a parallel plate capacitor in this system. Solving for $C$ yields a capacitance of approximately 5 fF. The resistance of the device is dominated by the resistance of the silicon ridges. The resistance of the device is found to be $3.12\text{K}\Omega$ using $R = \rho\frac{L}{A}$ where $\rho$ is the resistivity of silicon, $L$ is the length of the device and $A$ and is the cross sectional area of the
Figure 3.14: (a) This figure shows the result of a COMSOL eigenmode calculation of the symmetric mode of the optimized hybrid waveguide directional coupler exported into a Matlab script for post processing. (b) This figure shows the result of a COMSOL eigenmode calculation of the anti-symmetric mode of the optimized hybrid waveguide directional coupler exported into a Matlab script for post processing. (c) This figure shows the sum of the symmetric and anti-symmetric modes of the coupler which is the primary mode excited when light is input on a single arm of the coupler. (d) This figure shows the field in the coupler after the input field (shown in (b)) has propagated one coupling length, $L_c$. The power switches almost entirely to the other arm of the coupler and integrating the power on each arm yields an extinction ratio $(-10\log(P_{left}/P_{right}))$ of 29.5 dB.
Figure 3.15: The overlap between the driving voltage for the electro-optic polymer and the optical mode inside the device. The field is completely uniform over 70% of the optical field and can be reasonably expected to provide largely distortion free modulation of the optical mode.
silicon ridges. This yields an RC time constant of 17.5 ps, corresponding to a modulation speed of 57 Gbits/sec.

The capacitance of the device leads to a charge redistribution in the metal cap of the hybrid waveguides as given by \( q = CV \) where \( q \) is the excess charge in the metal, \( C \) is the capacitance of the device and \( V \) is the applied voltage. This new charge distribution leads to a change in the permittivity of the metal, which in turn causes a change in the propagation characteristics of the hybrid waveguides. However, the total change in permittivity is very small since the intrinsic free carrier concentration in gold is \( 1.5 \times 10^{29} \) and the change in carrier concentration in the metal due to the capacitor is only \( 2.25 \times 10^{22} \). Resolving the eigenmode equations for the hybrid waveguide switch coupler using the perturbed value of permittivity for gold given by the Drude model yields only a 0.005% change in the effective index of each mode which is quite small and can be neglected in further analysis.

Additionally, the device is moderately robust to fabrication errors of the bottom electrode. While the design calls for the bottom electrodes to be in contact with the silicon ridges, it can still function if there is a gap between them. The two main concerns are electrical contact and the voltage delivered to the active region of the device. A gap between the electrode and the silicon ridge would drastically increase the resistance of the system and lead to much lower operational speeds. To ensure electrical contact, the silicon should be slightly under-etched to leave a 50nm layer remaining on top of the silicon dioxide substrate. This method has been shown to successfully permit electrical contact with an etched silicon structure through the underlying silicon layer [44]. In this case, the resistance increases by 5K\( \Omega \) per 100nm of separation between the silicon ridge and the bottom electrode. Therefore, a 100nm gap between the electrode and the silicon ridge would triple the parasitic resistance and reduce the modulation speed by a factor of 3, down to about 20 Gbit/s. Also, a larger spacing between the bottom electrodes would lead to a lower electric field inside the device. Electrostatic simulations in COMSOL show that the voltage delivered to the active region of the device has an exponential falloff with metal-silicon separation with a characteristic
decay length of 300 nm. For a 100 nm gap, the applied voltage would have to be increased to 1.5 V in order to maintain the same switching performance. The power consumption of the device is mainly due to charging and discharging the capacitor. At 1V applied voltage, the power consumption is given by $P = 0.5fC V^2 = 0.15$ mW or 2.6 fJ/bit at 57 GBits/s. This proposed device satisfies the performance requirements of the next generation of optical communications and interconnects with its small footprint, fast modulation speed and low power consumption.
Chapter 4

Hybrid Waveguide Fabrication and Measurement

As shown in the previous chapter, hybrid waveguide theory predicts that devices based on silicon-insulator-metal (SIM) stacks can be used to construct novel and useful photonic devices. Additionally, devices based on SIM structures can create sub-wavelength light confinement while balancing the optical losses from the metals used in their construction. Active devices using this technology offer a drastic improvement in speed, power consumption and device footprint over active photonic devices using competing technologies such as ring resonator modulators [42], Mach Zehnder Interferometers [45], slow light photonic crystal switches [43] and carrier injected silicon ridge switches [46].

However, as with all new technologies, hybrid waveguides must be fabricated and tested in order to verify the theory behind them. The following chapter details a series of experiments performed at the University of Colorado at Boulder designed to verify the theoretical modeling of hybrid waveguide devices and confirm the optical properties of passive waveguide devices based on a hybrid waveguide platform.

All of the hybrid waveguide experiments were performed through post processing silicon-on-insulator (SOI) structures fabricated at the IMEC foundry in Belgium through an academic collaboration known as ePIXfab (http://www.epixfab.eu). IMEC is one of the research foundries in the European Union that provides high end silicon wafer processing. IMEC focuses primarily on optical communications projects and bio-sensing by providing a customizable passive silicon photonics platform to research groups around the world. A
customized mask was created by Dr. Zheng Li and Moustafa Mohammed and an 8 inch silicon wafer was patterned at IMEC through optical lithography and subsequently diced and delivered to us. The IMEC process utilized in this work has a minimum feature size of 130nm and a top silicon layer thickness of 220nm. This work focuses on one particular design, designated IMEC 4, which was subjected to a number of post processing steps in order to create a hybrid waveguide platform from the passive silicon photonic base structure.

The first experiment performed to verify the hybrid waveguide designs was a coupling and propagation loss experiment. In this experiment, the goal was to successfully couple light from free space into and then out of a hybrid waveguide structure using vertical grating couplers and also to measure the propagation losses of the system. The fabrication of the hybrid waveguide structures will be discussed in the following section, but after successfully fabricating a hybrid waveguide structure, light from an erbium fiber laser is coupled into the device, propagated through a variety of distances and outcoupled to an infrared detector so that the propagation loss can be calculated. Additionally, the light from a super luminescent LED is coupled into the structure, propagated a fixed distance and the real part of the effective index is extracted from the Fabry-Pérot fringes superimposed on the device’s transmission spectrum. After being measured, the devices were cleaved using a diamond scribe and observed using a scanning electron microscope to verify their physical characteristics.

The second experiment serves as both a verification of the behavior of hybrid waveguide directional couplers and also as a proof of concept for a switch based on hybrid waveguides with an electro-optic polymer spacer layer. Two devices were fabricated. Both devices are hybrid waveguide directional couplers, but one is coated with Poly(methyl methacrylate) (PMMA) - a common polymer used in many commercial applications [55] and the other is coated in SU-8 - an epoxy based negative photoresist [56]. Both polymers are stable at room temperature and transparent in the infrared, but they have different refractive indexes, which allows the two systems to demonstrate the kind of optical switching capabilities of a hybrid waveguide system based on an electro-optic polymer under different applied voltages.
The devices were fabricated to have the same physical parameters, with only the index of the two polymers differentiating the two devices. Light coupled into the PMMA device would emerge from the bar port of the device, while light coupled into the SU-8 device would emerge from the cross port. This would confirm both the power coupling characteristics of the hybrid waveguides and demonstrate the viability of an electro-optic switch based on a hybrid waveguide platform.

4.1 Fabrication

Hybrid waveguides are designed to be compatible with standard CMOS processing. One of the biggest advantages of hybrid waveguides as a platform for active photonic devices is the ease in which CMOS chips can be post processed to include hybrid waveguides. A patterned silicon on insulator platform can be converted into a hybrid waveguide platform with a few relatively simple steps. To create a hybrid waveguide device, a pre-patterned and diced silicon-on-insulator chip from the IMEC foundry in Belgium was used as a base. The chip was cleaned using acetone and isopropanol. Next, a thin layer of PMMA was spun onto the surface of the chip. In order to create the target layer thickness of 100 nm, a 2% solution of PMMA in anisole (PMMA A2) was spun at 1000 RPM for 60 seconds and then immediately baked at 100° C on a hotplate for 15 minutes to harden the polymer layer and remove any residual gasses. This created a layer 145 nm thick on the bare portion of the chip, measured using a DEKTAK profilometer [57]. An scanning electron micrograph of the cross section of these chips shows a polymer layer thickness of 85 ± 10 nm between the silicon ridges and top metal layer (see figure 4.1). Next, a 70 nm layer of gold was evaporated on top of the polymer using a thermal evaporator, followed by a 10 nm layer of chromium. The chromium serves to harden the top of the gold layer making it easier to cut using a focused ion beam without melting the metal layer. The thermal evaporator covers the entire surface of the chip with metal, blocking access to the pre-existing vertical grating couplers, so new couplers needed to be etched into the surface of the chip to allow light to be coupled into and
out of the hybrid waveguides. The gratings were designed using a combination of COMSOL multiphysics to find the expected effective index of the fabricated hybrid waveguides and a MATLAB script to find the period of the grating necessary to couple infrared light from the input fibers into and out of the guided modes. The period of the grating can be found using the following formula:

$$\Lambda_{\text{grating}} = \frac{\lambda_o}{\sqrt{n_{\text{eff}}^2 - \cos^2(\theta) - \sin(\theta)}}$$

(4.1)

Where $\Lambda_{\text{grating}}$ is the period of the coupling grating, $\lambda_o$ is the freespace wavelength of the test laser (an erbium fiber laser with a center wavelength at 1540nm), $n_{\text{eff}}$ is the predicted effective index of the hybrid waveguide mode ($n_{\text{eff}} = 2.1705$ for the fabricated hybrid waveguides with a 220nm tall by 450nm wide silicon ridge with 85nm of polymer and 70 nm of gold) and $\theta$ is the input angle of the fiber probes used to illuminate the gratings (10° from vertical). The calculated grating couplers have a period of 880nm. These couplers were milled into the metal using a focused ion beam system. The resulting device can be seen in figure 4.2.

The next set of devices required a more involved fabrication process due to the stricter constraints on the device’s performance. Straight waveguides can operate successfully and provide useful information over a wide range of fabrication parameters, but directional couplers require significantly stricter fabrication tolerances to ensure their proper function. The first new concern is the planarity of the polymer - metal interface. A non-planar surface between the two coupled waveguides will dramatically affect the operation of the directional coupler. The next concern is achieving a precise polymer layer thickness. The length of the directional coupler is fixed after fabrication, so to ensure that the PMMA coated device outputs light on the bar port and the SU-8 device outputs light to the cross port, a very specific polymer layer thickness must be achieved. The simple fabrication process used for the straight waveguides is not sufficient to ensure that these new constraints can be satisfied.
Figure 4.1: This figure shows a scanning electron micrograph of the cross section of a fabricated hybrid waveguide. The silicon ridge has a height of 220nm, the polymer layer is 145 nm ± 5 nm on the flat sections of the chip and 85 nm ± 10 nm above the silicon ridges.
Figure 4.2: This figure shows a scanning electron micrograph of a hybrid waveguide device with a vertical grating coupler with a period of 880nm.
Instead, a significantly thicker initial polymer layer must be deposited to ensure top surface planarity. Then the polymer must be etched down to the proper thickness using a reactive ion etch (RIE) to maintain that planarity. Fabrication of the first device began with a thorough cleaning of the surface using acetone and isopropanol. Next a thick layer of PMMA was spun onto the chip. 8% PMMA in anisol was spun at 5000 RPM for 60 seconds to create a 1200 nm thick polymer layer. The sample was then baked on a hot plate at 100°C for 20 minutes to harden and outgas the sample. DEKTAK measurements showed a surface roughness over the silicon waveguides of only 25 nm (a 90% reduction in surface roughness over the previous fabrication procedure). Next, the polymer was etched using an oxygen plasma at 150 Watts and 200 mTorr. After 180 seconds in the RIE, the PMMA layer was reduced from 1200 nm to the target thickness of 260 nm ± 5 nm. The next set of samples was spin coated with SU-8 2000.5. The samples were cleaned, coated with SU-8 and spun at 3000 RPM for 60 seconds. The samples were then baked at 95°C for 20 minutes to harden them. DEKTAK measurements showed that the SU-8 samples had a mean layer thickness of 570 nm and a surface roughness of 25 nm over the waveguides. These samples were also etched in the RIE. After 105 seconds in the RIE, the SU-8 layers were reduced from 570 nm to 260 nm ± 5 nm. After achieving the desired polymer layer thickness, the samples were coated with 60 nm of gold and 10 nm of chromium in the thermal evaporator. A new problem arose because the drastically reduced surface roughness limited the visibility of the waveguide structures under the metal and polymer when viewed through the SEM. To get around this issue, the samples were coated with AZ4620 photoresist [58] which was then patterned using a cross shaped mask with a 300 μm feature size. This process removed the AZ4620 photoresist everywhere except where the mask was placed. A mask aligner was used to place the feature directly over the directional coupler on the SOI substrate. After patterning, the sample was dipped into chromium etchant for 30 seconds and then gold etchant for 30 seconds. This removed the metal everywhere except directly over the directional coupler. The sample was then cleaned with acetone and isopropanol to remove the remaining photoresist, placed back into
the RIE for 120 seconds to take off the residual polymer not still protected by metal and finally put back into the thermal evaporator to deposit another 10 nm of gold and 10 nm of chromium over the entire structure to avoid surface charge accumulation issues in the SEM. This procedure ensured that the waveguide structures leading up to the directional coupler were visible under the SEM which allowed accurate placement of the coupling gratings onto the device. The processed directional coupler can be seen in figure 4.3 and the final device can be seen in figures 4.4 and 4.5.

4.2 Effective Index Validation

The first measurement made to verify the performance of the hybrid waveguides is an effective index calculation. The group index of the hybrid waveguides can be calculated from the Fabry-Pérot fringe spacing of the transmission spectrum of the devices. Group index is the speed at which a multifrequency signal propagates through a material. The group index is defined below:

\[ n_g = n_0 - \lambda_0 \frac{\delta n_0}{\delta \lambda_0} \]  

(4.2)

Where \( n_0 \) is the refractive index of the material at the vacuum wavelength \( \lambda_0 \).

The transmission was measured using an EXALOS fiber pigtailed super luminescent LED source [59] with a center wavelength at 1540.2 nm, a bandwidth of 64.2 nm and a peak power of 11.2 mW. The light is focused onto the grating coupler using a lensed fiber at an angle of 10° from vertical and collected at the output grating with the same. The signal is detected with an optical spectrum analyzer. The transmission spectrum of a 125 \( \mu \)m long hybrid waveguide section is shown in figure 4.6. The group index of the mode can be extracted from the fringe pattern superimposed on the transmission spectrum of the coupling grating using the following equation:
Figure 4.3: This figure shows the directional coupler before being processed with polymer and metal. The coupler is 64 µm long, the waveguides are 360 nm wide, 220 nm tall and the gap between them is 150 nm wide.
Figure 4.4: This figure shows an SEM image of the directional coupler processed with PMMA with inserts showing close up views of the grating couplers. A grating is milled through the metal at each of the four ports on the coupler. The directional coupler itself is 64 µm long and the ports are placed 180 µm apart.
Figure 4.5: This figure shows an SEM image of the directional coupler processed with SU-8 with inserts showing close up views of the grating couplers. A grating is milled through the metal at each of the four ports on the coupler. The metal is 300 µm across and was placed off center of the device by 60 µm. The directional coupler itself is 64 µm long and the ports are placed 180 µm apart.
\[ n_g = \frac{c}{2L\Delta F} \]  

(4.3)

Where \( n_g \) is the group index of the hybrid waveguide mode, \( c \) is the speed of light in vacuum, \( L \) is the length of the waveguide and \( \Delta F \) is the Fabry-Pérot fringe spacing in frequency space. Solving for the mode index of a hybrid waveguide with a length of 125 \( \mu \text{m} \) and a \( \Delta F \) of \( 1.8 \times 10^{12} \pm 8 \times 10^{10} \) Hz gives a group index of \( 3.2 \pm 0.1 \). COMSOL simulations of the fabricated hybrid waveguide give a group index of 3.1674 which is within the margin of error of the measurement.

The second step in calculating the mode index of the fabricated hybrid waveguide is to confirm the imaginary part of the refractive index. This is done by measuring the loss of the hybrid waveguide and fitting the data to an exponential to find the imaginary part of the propagation constant. Two devices were fabricated using identical procedures. Each device was etched with five vertical grating couplers that defined four sections of hybrid waveguides with different lengths. The waveguide is split into a 125 \( \mu \text{m} \), 150 \( \mu \text{m} \), 175 \( \mu \text{m} \) and 200 \( \mu \text{m} \) long section. Each section is illuminated with a fiber coupled erbium laser and the transmission is measured using a infrared photodetector. The transmission through the different sections was found then fit with an exponential to find the imaginary part of the propagation constant of the fabricated hybrid waveguide. The transmission of the two devices can be seen in figure 4.7. The average device transmission was fit with the equation \( e^{-0.0205x} \) with an \( R^2 \) value of 0.95 which corresponds to an imaginary propagation constant of 20098 m\(^{-1}\). The imaginary part of the propagation constant can be converted into the imaginary part of the effective index of the mode using the following equation:

\[ n_{\text{eff}}^* = \frac{\lambda_o}{2\pi\beta^*} \]  

(4.4)

where \( \lambda_o \) is the free space wavelength and \( \beta^* \) is the imaginary part of the propagation constant. This equation yields an imaginary index of 0.004958 \( \pm \) 0.0001. COMSOL simulations
Figure 4.6: This figure shows the transmission spectrum of a 125 µm hybrid waveguide. The period of the Fabry-Pérot fringes is $1.80 \times 10^{12} \pm 5\times10^{10}$ Hz. The data has been shifted so the peak transmission of the device is at 0dB. The signal to noise ratio of this measurement was found to be 2.
of the fabricated devices predict an imaginary effective index of 0.0048 which agrees well with the measurements. This corresponds to a propagation length (the distance the mode can propagate before decaying to $1/e$ of its original value) of 62.5 $\mu$m. COMSOL predicts a propagation length of 58.16 $\mu$m for a hybrid waveguide with a silicon ridge cross section of 220 x 450 nm and a PMMA spacer layer of 90 nm.

This experiment shows a strong correlation between the transmission characteristics of the fabricated waveguides and the theoretical calculations performed in COMSOL multiphysics. The effective index of the hybrid waveguide mode extracted from the experimental data detailed in the previous section matches the theory nicely.

### 4.3 Switching Length Confirmation

The next experiment necessary to demonstrate the adherence of the fabricated hybrid waveguides to theory one that confirms the properties of two coupled hybrid waveguides. The experimental framework used for this test is to fabricate two nearly identical hybrid waveguide directional couplers that differ only in the refractive index of the polymer used to create the spacer layer between the silicon ridges and the metal top layer. The optical parameters of the directional couplers have been designed to ensure that there is a measurable difference in the transmission of the two directional couplers. If the two devices agree with theoretical calculations, then the validity of the model will be further reinforced and it will also serve as proof of concept for an electro-optical switch based on a hybrid waveguide platform.

Both directional couplers were fabricated on an IMEC 4 chip from the +4 column. One device in particular was selected as an appropriate base for the hybrid waveguide directional coupler. This device occupies ports 33 and 34 on the chip and an SEM image of the device can be seen in figure 4.3. The device is 64 $\mu$m long and made of silicon ridge waveguides that are 360 nm wide and 220 nm tall with a gap between the two waveguides of 150 nm. The two polymers chosen for the switching demonstration were PMMA [55] and SU-8 [56].
Figure 4.7: This figure shows the transmission through 4 different lengths of a straight hybrid waveguide on two different chips fabricated under similar conditions. The transmission curves were fitted with an exponential and the imaginary part of the effective index of each device was extracted and compared to theory. The devices had an imaginary effective index equal to 0.004958.
Both polymers are transparent in the infrared, are stable once spun and baked, are non-toxic and fairly easy to work with and have significantly different indices of refraction at the test wavelength of 1540.2 nm (the center wavelength of the erbium laser probe source). At 1540.2 nm, PMMA has a refractive index of 1.45 [60] and SU-8 has an index of 1.575 [61], giving an index difference of 0.125 between the two polymers. This is quite useful for this experiment as it creates a significant difference between the propagation characteristics of the modes of the two different hybrid waveguides which in turn permits a short directional coupler to demonstrate switching. This is important because the propagation losses in the hybrid waveguides are fairly high (as seen in the previous section) and long devices would have very low transmission, making them difficult to measure.

Section 5.1 details the fabrication of the hybrid waveguide directional couplers used in this experiment. The end product was two hybrid waveguide devices with nearly identical physical dimensions. The dimensions were determined by an optimization run in COMSOL multiphysics to find the optimum polymer thickness necessary to demonstrate switching. Using the measured geometry of the IMEC4 devices, a series of eigenmode simulations were run using COMSOL to determine the mode indices of the symmetric and antisymmetric modes of the hybrid waveguide devices. The optimization parameter was polymer thickness and the goal of the optimization was to find a configuration of the devices that would demonstrate complete switching after 64 µm of coupled propagation. For a coupler of length 64 µm, the optimization found the ideal polymer thickness to be 260nm from the silicon dioxide substrate and 40 nm of polymer between the top of the silicon ridges and the metal top layer. This configuration produces a symmetric and antisymmetric hybrid waveguide mode with effective indices of $2.155904 + 0.00605i$ and $1.961126 + 0.007i$ respectively for the PMMA coated device and $2.251579 + 0.0071i$ and $2.068786 + 0.0077i$ for the SU-8 coated device. These effective indices can be converted into power coupling lengths (the distance needed for all of the power in one waveguide to couple to the other) using the following equation:
\[ L_c = \frac{\lambda_o}{2(n_{\text{sym}} - n_{\text{asym}})} \]  

(4.5)

where \( L_c \) is the power coupling length, \( \lambda_o \) is the free space wavelength, \( n_{\text{sym}} \) is the effective index of the symmetric mode and \( n_{\text{asym}} \) is the effective index of the antisymmetric mode.

Once the power coupling length for the PMMA and SU-8 devices has been calculated, the switch length can be found using the following equation which was derived in chapter 4:

\[ L_{\text{switch}} = \frac{L_{c1}L_{c2}}{2(L_{c1} - L_{c2})} \]  

(4.6)

where \( L_{\text{switch}} \) is the length of the switch, \( L_{c1} \) is the coupling length of the PMMA device and \( L_{c2} \) is the coupling length of the SU-8 device. Using the values for the coupling lengths found in the optimization, the switch length for a 260 nm layer of polymer is 61 \( \mu \)m which is nearly the same as the device length of 64 \( \mu \)m.

The two devices were fabricated as described in section 5.1 and the transmission of the PMMA device was measured using a fiber probe station with a fiber coupled erbium laser for illumination. Unfortunately, after completing the measurement on the PMMA device, the probe station had a software error that prevented further measurements. The SU-8 device was measured on a different probe station, hence the difference in power coupling efficiency between the two measurements. The results of the measurement can be seen in Table 4.1.

<table>
<thead>
<tr>
<th></th>
<th>PMMA Chip</th>
<th>SU-8 Chip</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Top Port</td>
<td>Bottom Port</td>
</tr>
<tr>
<td>Coupling Losses</td>
<td>-23.5 dB</td>
<td>-17.5 dB</td>
</tr>
<tr>
<td>Propagation Losses</td>
<td>-22 dB</td>
<td>-22 dB</td>
</tr>
<tr>
<td>Absolute Bar Transmission</td>
<td>-76 dB</td>
<td>-76 dB</td>
</tr>
<tr>
<td>Absolute Cross Transmission</td>
<td>-65 dB</td>
<td>-66 dB</td>
</tr>
<tr>
<td>Normalized Bar Transmission</td>
<td>-30.5 dB</td>
<td>-30.5 dB</td>
</tr>
<tr>
<td>Normalized Cross Transmission</td>
<td>-19.5 dB</td>
<td>-20.5 dB</td>
</tr>
</tbody>
</table>

The total transmission of the device is very low due in part to the loss of the devices but
mainly due to the very low coupling efficiency of the vertical grating couplers. The couplers are inscribed over 350 nm wide waveguides but illuminated with a 10 µm laser spot. The absolute best case coupling efficiency of the input coupler is equal to the ratio of the area of the waveguide to the laser spot:

$$\eta = \frac{A_{wg}}{A_{spot}} = \frac{10\mu m \times 0.350\mu m}{\pi (5\mu m)^2} = 4.5\%.$$  

However, in repeated use of the fiber probe station, we have observed an average end to end transmission efficiency for a fully illuminated grating of 10%. Combining these two efficiencies gives a predicted end to end transmission of 0.445%. Next we need to consider the propagation losses of the hybrid waveguides. The PMMA device has an average imaginary refractive index of 0.0065, which can be converted to a characteristic propagation length using the following formula:

$$L_{prop} = \frac{1}{\beta} = \frac{\lambda_o}{2\pi n_{eff}^*} \quad (4.7)$$

where $L_{prop}$ is the propagation length, $\beta$ is the propagation constant of the hybrid mode, $\lambda_o$ is the free space wavelength and $n_{eff}^*$ is the imaginary part of the effective index of the hybrid mode. This equation gives a propagation length of 35 µm. The device is 180 µm long, which equates to 5.1 propagation lengths. This causes the field to decay to $e^{-5.1}$ of its original value. Combining all of these efficiency factors together yields an expected end to end transmission of -45.5 dB. The second fiber probe station has a smaller spot size (2.5 µm vs. 10 µm) and a different imaging system which leads to the different efficiency observed in the SU-8 device. The smaller spot size of the second system would give an expected end to end transmission of -39.5 dB. Additionally, the two measurement systems had different noise levels. The noise floor for the PMMA device was $\approx -76$ dB while the noise floor for the SU-8 device was -90 dB. The net transmission of the two devices agrees well with expectations.

This results clearly demonstrate the expected coupling effects. Light input to the PMMA device emerged from the cross port and light input to the SU-8 device emerged from the bar port as predicted by theory. This confirms the coupling length calculations performed in COMSOL. A perturbation of the index of the dielectric spacer layer in a hybrid waveguide
directional coupler causes power switching between the two waveguides. While this work is not a truly active device, the experiments agree well with theory, proving the concept for the switch to be sound.
Due to the ever increasing demand for computational power and the increasing cost and difficulty of down-scaling the critical dimensions of on-chip components, core processing has become the dominant mechanism for processor power scaling in recent years. Multi-core systems can provide great advantages in terms of computational power, but their added complexity necessitates a complex interconnect system to handle inter-core communications. Currently, electrical interconnects have been able to keep up with the bandwidth demands of modern multi-core systems, but we are fast approaching the practical limits of metal wire based interconnects in terms of speed, bandwidth, power consumption and complexity. Optical interconnects are promising replacements for their electrical counterparts, but a number of technical challenges and a lack of compact, high-speed, low power active photonic devices limits their deployment.

In this dissertation we have proposed a new kind of optical switch based on a hybrid silicon-metal waveguide platform. Hybrid waveguides are a novel waveguide structure that achieves the sub-wavelength optical mode confinement of plasmonics while mitigating the device losses. They also demonstrate a number of interesting properties such as allowing for the integration of electro-optic materials, high sensitivity to perturbations in the optical and geometric properties of the waveguide, direct electrical access to the material in the gap between the silicon ridge and the metal cap, simple fabrication and CMOS compatibility. Due to these properties, hybrid waveguides are promising structures for creating active photonic
devices such as modulators and switches.

The design for a hybrid waveguide electro-optic switch was presented and its properties were analyzed. Using a hybrid waveguide directional coupler as a design basis, an electro-optic switch with a 30 $\mu m^2$ physical footprint was designed. Additionally, the performance of the switch was analyzed and the maximum switching speed was found to be 57 Gbit/s while operating at $\pm 1V$. The switch displays an extraordinarily low power consumption of 2.6 fJ/bit while operating at its maximum speed as well as 29.5 dB of extinction between the bar and cross states and only 1.6 dB of propagation losses owing to its very short length. This device appears to satisfy many if not all of the requirements for switches need for the next generation of optical interconnects [2].

We have also experimentally confirmed many of the optical properties of hybrid waveguides. The measured real and imaginary parts of the effective index of the hybrid were shown to be very good agreement with Finite Element (FEM) simulations. Also, an experiment mimicking the operation of an electro-optic switch was carried out and the results were extremely promising. Two nearly identical hybrid waveguide directional coupler devices were fabricated, varying only in the refractive index of the polymer spacer layer that separates the silicon ridges and the metal cap. This mimics the change that would occur in an electro-optic polymer in the presence of an applied voltage. The transmission of each device was measured. The device fabricated with the lower index polymer (PMMA) showed bar port transmission of $-29.5$ dB and cross port transmission of $\approx -20$ dB while the high index polymer device (SU-8) had a bar port transmission of $\approx -22dB$ and a cross port transmission of $-50$ dB. This demonstrates clear switching behavior through a variation in the index of the low index spacer layer and confirms the coupling length calculations performed using COMSOL.

There is still much work to be done on hybrid waveguides. They are a new and exciting type of structure in silicon photonics with a lot of promise for future use in many kinds of devices. Before that promise can be fulfilled though, a number of tasks must first
be accomplished. First, a truly active hybrid waveguide switch using electrically driven EO polymers must be built and characterized. In order to integrate hybrid waveguides into existing photonic networks, the coupling between standard silicon waveguides and hybrid waveguides must be optimized and integrated into the designs of hybrid devices. Also, the thermal and process variation of the devices must be understood and the tolerance of the system to these variations must incorporated into the design of any future devices. Finally, hybrid waveguides need to be fully integrated into photonic networks and deployed on a variety of platforms such as high performance computers, data centers and even consumer electronics.

There are many obstacles facing the development of photonic networks, but their future seems bright and full of possibility. Novel structures such as hybrid waveguides are pushing the envelope of what can be accomplished on the small scale with optical interconnects and it seems to be only a matter of time before computing takes the next big leap forward by implementing fast, power efficient optical interconnects to facilitate the new computer paradigm of processor-core scaling.
Bibliography


[60] http://refractiveindex.info/?group=PLASTICS&material=PMMA

