Critical Design Comparisons For Flagship Photonic/ Optical Directional Couplers in the Wavelength Range 1310–2000 nm Deployed in WDM Applications

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Abstract

Photonic or optical directional couplers (PDCs) are passive devices that couple light through waveguides or fibers. They are used to split, combine, or redirect optical signals while maintaining directionality, similar to their microwave and RF counterparts. They play a vital role in the applications of photonic devices and systems. Optical couplers can be the interface between devices in a system or can be essential devices themselves. The most straightforward yet important application is to route optical waves around for coupling different devices. Sophisticated applications include devices such as polarization converters, mode converters, guided-wave beam splitters, beam combiners, directional couplers, branch couplers, wavelength filters, wavelength multiplexers, and so on. These devices are often categorized based on their design and operating principles. Some crucial categories include Single-mode and Multimode Fused Fiber Couplers; Planar Waveguide Directional Couplers; Slab Waveguide Directional Couplers; Photonic Crystal Directional Couplers, Silicon-on-Insulator (SOI) Directional Couplers; Tapered Waveguide Directional Couplers; Nonlinear Optical Directional Couplers and Hybrid Directional Couplers.

This thesis examines research articles published after 2010 to examine PDCs functioning in the infrared spectrum's O/C band (1310-2000 um) to specifically compare performances of 1310 - 2000 nm Generic Diplexers, MMIs (Multimode Interference), Y-Junction, and MZI optical couplers (the subject PDCs of this research study) with Wavelength Division Multiplexing (WDM) applications across a range of industrial and research use cases. To discover and choose relevant material; the study employs keywords such as ”SWG” (Silicon Waveguides), ”DC” (Directional Couplers), and ”MZI” (Mach-Zehnder Interferometer). The main goal is to compare different design parameters inside these photonic directional coupler variants, such as waveguide diameter, materials, input/output coupling strategies, and so on. By examining these factors, the research intends to create a Figure of Merit, a quantitative indicator that evaluates performance across the three subject PDC types. This Figure of Merit is an essential tool for assessing and comprehending the efficiency and efficacy of PDCs operating within this specific wavelength range. In sum, the thesis attempts to review the elements of design and operation circumstances of three of the commonest expressions of photonic directional couplers – Photonic Diplexers, Y-Junction, MMI and MZI are the subjects of this dissertation's study.

Abrégé

Les coupleurs photoniques ou optiques directionnels (PDC) sont des dispositifs passifs qui couplent la lumière à travers des guides d'ondes ou des fibres. Ils sont utilisés pour diviser, combiner ou rediriger les signaux optiques tout en conservant la directivité, similaire à leurs homologues micro-ondes et RF. Ils jouent un rôle essentiel dans les applications des dispositifs et systèmes photoniques. Les coupleurs optiques peuvent être l'interface entre les appareils d'un système ou peuvent être eux-mêmes des appareils essentiels.Le L'application la plus simple mais la plus importante consiste à acheminer les ondes optiques pour couplage de différents appareils. Les applications sophistiquées incluent des dispositifs tels que la polarisation convertisseurs, convertisseurs de mode, séparateurs de faisceaux à ondes guidées, combineurs de faisceaux, directionnels coupleurs, coupleurs de dérivation, filtres de longueur d'onde, multiplexeurs de longueur d'onde, etc.Ces les appareils sont souvent classés en fonction de leur conception et de leurs principes de fonctionnement.Certains cruciaux les catégories comprennent les coupleurs de fibres fusionnées monomodes et multimodes ; Guide d'ondes planaire Coupleurs directionnels ; Coupleurs directionnels de guide d'ondes en dalle ; Cristal photonique directionnel Coupleurs, coupleurs directionnels en silicium sur isolant (SOI); Guide d'ondes conique directionnel Coupleurs ; Coupleurs directionnels optiques non linéaires et coupleurs directionnels hybrides.

Cette thèse examine les articles de recherche publiés après 2010 pour examiner les PDC fonctionnant dans la bande O/C du spectre infrarouge (1310-2000 um) pour comparer spécifiquement performances des diplexeurs génériques de 1310 à 2000 nm, des MMI, de la jonction en Y et des optiques MZI coupleurs (les PDC sujets de cette étude de recherche) avec multiplexage par répartition en longueur d'onde (WDM) dans une gamme de cas d'utilisation industriels et de recherche. A découvrir et choisir le matériel pertinent ; l'étude utilise des mots-clés tels que « SWG » (Silicon Guides d'ondes), « DC » (Coupleurs directionnels) et « MZI » (Interféromètre Mach-Zehnder).L'objectif principal est de comparer différents paramètres de conception à l'intérieur de ces directionnels photoniques. variantes de coupleur, telles que le diamètre du guide d'ondes, les matériaux, les stratégies de couplage entrée/sortie, et ainsi de suite. En examinant ces facteurs, la recherche vise à créer une figure du mérite, une indicateur quantitatif qui évalue les performances dans les trois types de PDC. Cette figure de mérite est un outil essentiel pour évaluer et comprendre l'efficacité et la l'efficacité des PDC fonctionnant dans cette plage de longueurs d'onde spécifique. En résumé, la thèse tente d'examiner les éléments de conception et les circonstances d'exploitation de trois des expressions les plus courantes de coupleurs directionnels photoniques – Diplexeurs photoniques, jonction en Y, MMI et MZI sont les sujets d'étude de cette thèse.

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Chapter 1

Introduction

1.1 Motivation for the Dissertation Study

I have been interested in quantum computing hardware design and engineering for the past year and would like to explore an opportunity to do a Ph.D. on this theme. Since PDCs are integral to typical QC hardware, this dissertation coursework is an opportunity to study and examine these devices and their evolution in greater depth and develop a perspective on their conceptual and engineering design. I chose to focus on Diplexers, Y-Junction, MMI, and MZI in particular in this thesis because we know these variants form a fundamental component in quantum photonic circuits, helping to manipulate and guide photons in quantum information processing tasks.

The photonic Diplexers, for instance, are used in Quantum Key Distribution (QKD), Quantum Networking, Quantum Sensing, Quantum Metrology, Quantum Signal Processing, and Quantum Teleportation, to cite some of the critical applications. On the other hand, the Y-junctions can be used for splitting and combining quantum states of photons, which is essential for various quantum operations, such as quantum gates and interference experiments in quantum computing and quantum communication systems. In a similar vein, MMI variants of PDCs are integrated into quantum photonic circuits to split, combine, or route photons.They are deployed in tasks like quantum state preparation, quantum interference, and photon multiplexing. MMIs help manipulate and control the quantum states of photons, making them valuable components in quantum information processing systems. MZI, similarly, plays a crucial role in various quantum operations, such as quantum gates, interferometry, and quantum state manipulation in quantum photonic circuits. MZIs are valuable for implementing quantum algorithms and performing quantum information processing tasks.

Hence, I thought, besides making a teeny-weeny contribution to the current body of knowledge on contemporary trends among PDC designers, researchers, and engineers, I could also generate a decent body of knowledge in this subject for my personal use later when I commence my PhD work: It would be a headstart for me.

1.2 Dissertation Objective

In this dissertation thesis, I have attempted to study contemporary research and development on the design of photonic directional couplers with a special focus on three particular variants - types: Photonic Diplexers, Y-Junction DCs, the Multi-Mode Interference (MMI) DCs, and the Mach Zedner Interferometer (MZI). I have tracked and examined research papers written since 2010 on PDCs in the 1310 - 2000 nanometer (nm) wavelength operational range on these four subject PDC types and those with predominant deployment for Wavelength Division Multiplexing (WDM) in contemporary industrial applications in communication, sensing, and signal monitoring, among others.

Specifically, I aim the following in this thesis by studying reference books on photonic devices - and, more specifically - examining 35 different research papers on the theme of photonic and optical directional couplers:

- To create a reckoner on the categories or branches along which photonic directional couplers seem to have evolved since 2010.
- To understand the typology of variants of PDCs currently in use around the world.
- To summarize the key concepts around which PDCs are generally designed and engineered today.
- To highlight key design features and technical attributes of some of the more cited photonic diplexers, Y-Junction, MMI, and MZI DCs (subjects of this research study) developed by researchers and engineers since 2010.
- To discuss and tabulate design and performance comparisons of some of the more cited expressions of the three subject PDCs globally.

Chapter 2

Background of Photonic Directional Couplers

2.1 History of Photonic Directional Couplers (PDC)

2.1.1 Development Timeline of Photonic Directional Couplers

Photonic directional couplers first emerged in the mid-20th century when researchers and engineers began exploring waveguide-based optical devices and their possible applications in signal sensing, monitoring, measurement, processing, and transmission. The following is the crude timeline of the evolution of PDCs:

The First Optical Waveguides (the 1950s-1960s):

The concept of optical waveguides, as contraptions that can guide and control the propagation of light, was first established in the 1950s and 1960s. These early waveguides can be seen to be foundationally critical for the development of photonic devices in later decades [26].

The Optical Directional Couplers Concept (1970s):

The concept of an optical directional coupler (DC) evolved in the 1970s, drawing from the principles of electrical transformers that have been used for more than a century. The DC was developed as a device that could possibly split and combine optical signals.

Development of Semiconductor Waveguides (1980s):

With the advent of semiconductors, the construction of optical waveguides underwent a mini-revolution of sorts in the 1980s, ensuring far better control of the channelizing, processing, and transmission/ propagation of optical signals. [27]

Evolution of Integrated Photonics (Since the 1990s to Present):

The development of integrated photonic circuits for use in communication infrastructure hardware opened a new era of importance for photonic directional couplers, as they became integral to all photonic circuits on single microchips.

Advancements in Nanophotonics (Since 2000s to Present):

The need to miniaturize photonic devices was met nicely by photonic directional couplers as it made it possible to use the concepts of Nanophotonics to manipulate light at the nanoscale.

Silicon Photonics (2000s-Present):

Silicon-based devices have obtained popularity over the last few decades thanks to their unquestioned compatibility with contemporary semiconductor fabrication processes. Silicon photonics, thus, has taken the evolution of photonic directional couplers to an interesting new tangent.

Ongoing/ Current Applications and Research:

Today, research in photonics and PDC aims to improve their performance, reduce losses, and expand their range of applications beyond telecommunications, optical computing, and sensing, and find use in quantum computing and artificial intelligence.

The evolution of photonic directional couplers is closely tied to the broader field of photonics and continues to be an area of active research and development, with the potential to revolutionize how we process and transmit information using light.

2.1.2 Evolution in Design of Photonic Directional Couplers

Since the early 1970s, when the first photonic directional couplers started emerging, they have undergone several cycles of evolution in their structure, design, configuration, composition, shape, and size. Some key milestones in this evolution can be traced as follows [28]:

Straight Waveguide Couplers (1970s):

The very first directional couplers primarily featured straight waveguides, and the coupling between them was generally accomplished through what we know as evanescent field overlap.

Periodic-Structured/ Grating Couplers (1980s):

Grating couplers deployed periodic structures (gratings) to couple light from one waveguide to another, improving the coupling efficiency between waveguides and enhancing the device's performance.

Multimode Interference (MMI) Couplers (1990s):

MMI couplers quickly became popular thanks to their ability to split and combine optical signals efficiently by achieving directional coupling through exploiting the interference between multiple guided modes in a waveguide.

Tapered Waveguides (the 2000s):

To reduce mode mismatch and improve the coupling ratio to increase coupling efficiency, researchers experimented successfully with waveguides having varying width or thickness - essentially tapering tapering them.Tapered directional couplers have since enjoyed widespread applications across a range of photonic devices.

Photonic Crystal Directional Couplers (2000s) [29]:

Under their hood, these couplers have periodic dielectric structures - like crystals - integrated into their waveguides. Photonic crystal structures are known to facilitate more accurate control of light propagation and coupling, ensuring much-improved coupling ratios.

Silicon Photonics Integration (2010s-and ongoing):

Silicon photonics has revolutionized the design of photonic directional couplers. These couplers are now often integrated into silicon-based photonic integrated circuits (PICs), enabling mass production and miniaturization.

Nonlinear Directional Couplers (Ongoing):

A stream of photonic research has been dedicated to developing nonlinear directional couplers that can manipulate light signals in hitherto newer ways to improve coupling performances in applications like all-optical switching and wavelength conversion.

Metamaterials and Plasmonics (Ongoing): [30]

The need to have more compact and versatile PDCs has turned researchers to experimenting with emerging materials and concepts like metamaterials and plasmonics, which can potentially control light at subwavelength scales.

Quantum Photonic Directional Couplers (Ongoing):

Quantum photonics researchers are increasingly seeking to calibrate directional couplers to work with single photons to improve efficiencies in quantum information processing quantum key distribution.

The design of photonic directional couplers continues to evolve, driven by advancements in materials, fabrication techniques, and novel applications.These developments are essential for improving the efficiency and versatility of photonic devices in various fields, from telecommunications to quantum optics.

2.2 The Physics of PDCs

Optical directional couplers rely on several key physics principles to manipulate and control the light flow within waveguides. Here are the fundamental physics principles used in optical directional couplers [31] :

Waveguiding:

Waveguides are structures that confine and guide light.They are typically made of materials with a higher refractive index than their surroundings.The principle of total internal reflection is key to waveguiding.Light is guided within the waveguide core, preventing it from escaping and enabling it to be manipulated.

Interference:

Interference is a fundamental wave phenomenon that occurs when two or more light waves interact. In optical directional couplers, interference controls the coupling and distribution of light between the waveguides. Constructive interference results in efficient optical power transfer, while destructive interference leads to minimal or no transfer.

Phase Matching:

To achieve constructive interference and efficient power transfer between waveguides, it is crucial to maintain phase matching. Phase matching ensures that the optical waves in different waveguides have similar phase relationships and can combine constructively. Phase matching is determined by factors such as waveguide dimensions, refractive indices, and wavelength.

Evanescent Fields:

In various directional couplers, light is transferred from one waveguide to another through the evanescent fields extending beyond the waveguides' core. The amplitude of the evanescent fields decays exponentially with distance from the core, and their interaction allows for energy exchange between the waveguides.

Resonance:

Some directional couplers are designed based on resonant principles. By controlling the length and properties of the coupling region, the coupler can be tuned to resonate at specific wavelengths. At resonance, the coupling efficiency is maximized, allowing for efficient power transfer.

Energy Conservation:

Energy conservation is a fundamental principle that ,stating that the total energy remains constant for a closed system. In optical directional couplers, this principle ensures that the energy of the incoming optical signal is conserved during the coupling process, whether split between waveguides or transferred from one waveguide to another.

Mode Theory:

Waveguides support different optical modes, which are specific electromagnetic field distributions within the waveguide. Understanding the properties and behavior of these modes is critical for designing and analyzing directional couplers. Mode theory considers factors like mode dispersion and mode coupling in the waveguides.

Propagation Constants:

Propagation constants measure how fast a specific mode propagates through a waveguide. These constants are determined by the materials' refractive indices and the light's wavelength.In directional couplers, differences in propagation constants between the waveguides are manipulated to control the coupling efficiency.

Material Properties:

The refractive index of the materials used in waveguides plays a crucial role in the operation of directional couplers. The choice of materials affects the waveguide properties, including waveguide dispersion and the critical angle for total internal reflection.

Optical Power Conservation: [32]

Conservation of optical power ensures that the total power in the system remains constant. This principle is essential for designing directional couplers to efficiently distribute or combine optical power without significant loss.
In summary, optical directional couplers use the principles of waveguiding, interference, phase matching, evanescent fields, and other optical properties to manipulate and control the flow of light in integrated photonic devices. Understanding and optimizing these principles are essential for designing and operating effective optical directional couplers in various optical communication and photonics applications.

2.3 The Equations Important in PDC Designing

The design of photonic directional couplers involves various equations related to waveguide theory, electromagnetic optics, and coupling theory. Here are some fundamental equations relevant to designing photonic couplers:

Coupling Length (L_c) :

$$[L_c = \frac{\pi}{2 \cdot \text{Coupling Coefficient}}] \tag{2.1}$$

where, L_c is the interaction length over which energy is transferred between two coupled waveguides or optical components.Units are expressed in meters(m).

Coupling Coefficient (κ):

$$[\kappa = \frac{\pi}{2 \cdot \text{Coupling Length}}] \tag{2.2}$$

where, κ is the measure of efficiency with which optical power is transferred from one waveguide to another in a coupled system.It has no units.

Coupling Ratio (CR):

$$[CR = \frac{P_{\text{output, coupled}}}{P_{\text{input}}}] \tag{2.3}$$

where, CR represents the ratio of output power coupled ($P_{\text{output, coupled}}$) to a specific input channel (P_{input}).It has no units.

Power in Each Waveguide (P1 and P2)

$$[P_1 = P_{\text{input}} \cdot \frac{1+\kappa}{2}][P_2 = P_{\text{input}} \cdot \frac{1-\kappa}{2}] \tag{2.4}$$

Insertion Loss (IL):

$$[IL = -10 \cdot \log_{10}\left(\frac{P_{\text{output, through}}}{P_{\text{input}}}\right)] \tag{2.5}$$

where, (IL) in an optical system is a measure of the decrease in power when light is transmitted through a device, where $P_{\text{output, through}}$ is the output power.It is expressed in decibels (dB).

Extinction Ratio (ER):

$$[ER = 10 \cdot \log_{10}\left(\frac{P_{\text{Desired Signal}}}{P_{\text{Unwanted signal}}}\right)] \tag{2.6}$$

where,(ER) is defined as the ratio of optical power between the "on" state (the power of the desired signal) and the "off" state (the power of the unwanted signal or background noise).It has no units.

Isolation (ISO):

$$[ISO = -10 \cdot \log_{10}\left(\frac{P_{\text{output, cross}}}{P_{\text{input}}}\right)] \tag{2.7}$$

where ISO in the optical systems refers to the degree to which a signal in one part of the system is prevented from affecting or interfering with signals in another part, where $P_{\text{output, cross}}$ is the optical power exiting the other port.It is expressed in decibels (dB).

Beat Length (L_b):

$$[L_b = \frac{\lambda}{2 \cdot n_{\text{eff,difference}}}] \tag{2.8}$$

where, L_b is the distance over which the phase of two optical waves of slightly different frequencies, known as the beat frequency, completes one full cycle, where λ is the wavelength of light in the fiber and $n_{\text{eff,difference}}$ is the absolute value of the difference in refractive indices for the two orthogonal polarizations.It is measured in meters.

Effective Refractive Index :

$$(n_{\text{eff}}) = [n_{\text{eff}} = \frac{c}{v_{\text{group}}}] \tag{2.9}$$

where,n_{eff} is the ratio of (c - speed of light in vaccum) and (v_{group} - group velocity),has no units.

Phase Difference ($\Delta\phi$) in Coupling Region:

$$[\Delta\phi = \frac{2\pi}{\lambda} \cdot n_{\text{eff,difference}} \cdot L_{\text{c}}] \tag{2.10}$$

where,$\Delta\phi$ is a measure of the angular shift between two waveforms or signals, where .It is measured in Radians.

Other Equations Important for Engineering of Photonic Devices

Photonic devices are governed by various equations and principles. Here are some important equations and concepts relevant to photonic devices:

Maxwell's Equations:

These four equations describe the behavior of magnetic and electric fields in space and time. They are fundamental to understanding the propagation of electromagnetic waves, including light.

i. Gauss's Law for Electricity

Gauss's Law for Electric Fields

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{1}{\epsilon_0} \oint \rho \, dV \tag{2.11}$$

In other words, this equation states that the electric flux over a closed surface equals the charge confined by the surface divided by the electric constant (ϵ_0). It describes how electric fields emanate from electric charges, where $\mathbf{E}$ is the electric field vector, ϵ_0 is the permittivity of free space, $d\mathbf{A}$ represents a differential area vector, ρ is the charge density.

ii. Gauss's Law for Magnetism

$$\oint \mathbf{B} \cdot \mathbf{dA} = 0 \tag{2.12}$$

This equation expresses that the magnetic flux through a closed surface is always zero; there are no magnetic monopoles, where **B** is the magnetic field vector.

iii. Faraday's Law of Electromagnetic Induction

$$\oint \mathbf{E} \cdot \mathbf{dl} = -\frac{d}{dt} \int \mathbf{B} \cdot \mathbf{dA} \tag{2.13}$$

This equation describes how a changing magnetic field induces an electromotive force (EMF) in a closed loop, where **dl** is a differential length vector.

iv. Ampère's Circuital Law with Maxwell's Addition

$$\oint \mathbf{B} \cdot \mathbf{dl} = \mu_0 \left(\int \mathbf{J} \cdot \mathbf{dA} + \varepsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot \mathbf{dA} \right) \tag{2.14}$$

This equation relates the circulation of the magnetic field around a closed loop to the sum of the conduction current (J) passing through the loop and the rate of change of electric flux, where **J** is the current density, μ_0 is the permeability of free space.

Wave Equation:

The wave equation is a partial differential equation that explains how electromagnetic waves, including light, propagate through space. It's a key equation in optics. The general form of the one-dimensional wave equation is:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{2.15}$$

Here's what these terms mean: $(\frac{\partial^2 u}{\partial t^2})$ represents the second partial derivative of the function u concerning time (t), which describes how the wave changes over time. $(\frac{\partial^2 u}{\partial x^2})$ represents the second partial derivative of u about spatial coordinate x, describing how the wave varies in space. c is the wave speed, which depends on the properties of the medium in which the wave is propagating. For electromagnetic waves in a vacuum, c is the speed of light (approximately 3 x 10^8 meters per second).

Snell's Law:

This Law describes the relationship between the refraction and angle of incidence when light passes through the interface between two different materials. It's essential for understanding how light changes direction at boundaries. It is a fundamental law in optics and is crucial for understanding how light changes direction at the interface between two materials.

Snell's Law is typically expressed as follows:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{2.16}$$

Where n_1 is the refractive index of the medium from which the light is incident, θ_1 is the angle of incidence i.e., the angle between the incident light ray and the normal (perpendicular line) to the surface at the point of incidence, n_2 is the refractive index of the medium from which the light is entering, θ_2 is the angle of refraction i.e., the angle between the refracted light ray and the normal to the surface inside the second medium.

Fermat's Principle:

This principle states that light follows the path of least time when propagating between two points. It's the basis for understanding the principles of reflection and refraction. It can be expressed mathematically as a variational principle. The equation representing Fermat's Principle is based on the concept of optical path length and is given as:

$$\delta\left(\int_C \eta \cdot d\boldsymbol{s}\right) = 0 \tag{2.17}$$

Where δ is the symbol representing a variation or change in the expression, $\int$ is the integral sign indicating that we are considering the integral of the following expression over a specific path, η is the refractive index of the medium through which light propagates.

Fresnel Equations:

These equations describe the reflection and transmission of light at the boundary between two media with different refractive indices.They are crucial for designing and understanding optical coatings and anti-reflection coatings.

There are two primary Fresnel equations:

one for reflection and transmission. The equations are specific to the polarization of light, either s-polarization (perpendicular or transverse electric, TE) or p-polarization (parallel or transverse magnetic, TM).

Fresnel Equations for Reflection:
a. For s-polarized light (TE): Reflection coefficient

$$(r_s) = \left(\frac{n_1\cos(\theta_1) - n_2\cos(\theta_2)}{n_1\cos(\theta_1) + n_2\cos(\theta_2)}\right)^2 \tag{2.18}$$

b. For p-polarized light (TM): Reflection coefficient

$$(r_p) = \left[\frac{n_2\cos(\theta_1) - n_1\cos(\theta_2)}{n_2\cos(\theta_1) + n_1\cos(\theta_2)}\right]^2 \tag{2.19}$$

In these equations, n_1 and n_2 are the refractive indices of the two mediums, and θ_1 and θ_2 are the angles of incidence and refraction, respectively.

Fresnel Equations for Transmission:
a. For s-polarized light (TE): Transmission coefficient

$$(t_s) = 1 + r_s = \frac{2n_1\cos(\theta_1)}{n_1\cos(\theta_1) + n_2\cos(\theta_2)} \tag{2.20}$$

b. For p-polarized light (TM): Transmission coefficient

$$(t_p) = 1 - r_p = \frac{2n_1\cos(\theta_1)}{n_2\cos(\theta_1) + n_1\cos(\theta_2)} \tag{2.21}$$

The transmission coefficient includes the reflection coefficients r_p, r_s because energy is conserved, and any light not reflected is transmitted.

Beer-Lambert Law:

This Law relates light absorption to the concentration of a substance in a medium. It's commonly used in spectroscopy and photonic sensors.

Planck's Law:

This equation relates the energy of a photon to its wavelength. It's fundamental in understanding the energy and spectral characteristics of light.

Einstein's Photoelectric Equation:

This equation explains the relationship between the energy of incident photons and the kinetic energy of discharged electrons in the photoelectric effect, demonstrating the quantization of light energy.

Diffraction Grating Equation:

This equation relates the angles at which different orders of diffracted light appear when light passes through a diffraction grating, helping in spectral analysis.

Fourier Transform:

The Fourier transform is used to analyze light spectrum, breaking it down into its constituent frequencies, which is vital in spectroscopy and signal processing.

Gaussian Beam Propagation Equation:

This equation describes the behavior of Gaussian laser beams as they propagate through optical systems.

Kerr Effect Equation:

The Kerr effect describes the change in the refractive index of a material with changes in the intensity of light passing through it. The equation is crucial in nonlinear optics.

Schrödinger Equation (Quantum Mechanics):

In photonic devices involving quantum effects, the Schrödinger equation describes the behavior of particles, including photons, in quantum systems.

2.4 Categories of PDCs

Optical directional couplers are optical devices used to split, combine, or redirect optical signals while maintaining directionality, similar to their microwave and RF counterparts. These devices are often categorized based on their design and operating principles. Here are some common categories of optical directional couplers:

1. **Fused Fiber Couplers: [33]**
   - Single-Mode Fused Fiber Couplers: These couplers are made by fusing and tapering single-mode optical fibers. They can be used for splitting or combining optical signals and are widely used in telecommunications, fiber optic sensors, and optical networks.
   - Multimode Fused Fiber Couplers: These couplers are designed for multimode fibers and are used in applications involving multiple optical modes. They are less common compared to single-mode couplers.

Figure 2.1: 1310-1550nm-high-power-sm-fiber-fused-coupler [23].

2. **Planar Waveguide Directional Couplers:**
   - Y-Branch Couplers: Y-branch couplers are planar waveguide devices that use a Y-shaped branching structure to split or combine optical signals. They are commonly used in integrated optical circuits, optical switches, and power splitters.
   - 3 dB and 90/10 Couplers: These couplers are designed to divide the input signal into two output ports with a 3 dB (50/50) power split or a 90/10 power split, respectively. They are often used in optical networks and sensing applications. Below figure [34] shows an asymmetric Y-branch.

3. **Slab Waveguide Directional Couplers:**
   - Directional couplers use a slab waveguide [24] design, often with lithium niobate or other electro-optic materials. They are employed in various applications, including modulators and switches.

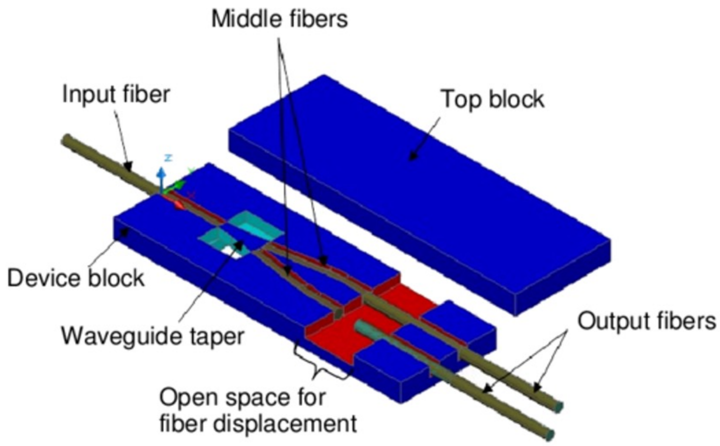

Figure 2.2: CAD-design-for-acrylic-based-asymmetric-Y-branch-POF-coupler.

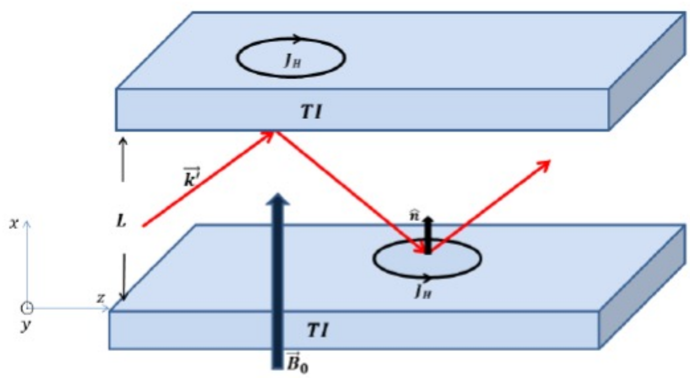

Figure 2.3: Slab-waveguide [24]-with-aperture-length-L-and-TIs-walls.

4. **Photonic Crystal Directional Couplers: [35]**

- Photonic crystal directional couplers use photonic crystal structures to control the light flow. These devices can have unique and customizable dispersion and bandgap characteristics, making them valuable for applications like dispersion compensation and wavelength filtering.

5. **Silicon-on-Insulator (SOI) Directional Couplers:**
    - SOI directional couplers are based on a silicon-on-insulator platform. They are commonly used in photonic integrated circuits, offering compact and efficient light manipulation.

6. **Tapered Waveguide Directional Couplers:**
    - Tapered waveguide directional couplers use gradual changes in waveguide width to split or combine optical signals. They are often used for coupling light in and out of waveguides or optical fibers.

7. **Acousto-Optic Directional Couplers:**
    - Acousto-optic directional couplers use acoustic waves to modulate the refractive index of an optical waveguide, allowing for dynamic control of the coupling ratio. They are used in various applications, including tunable filters and switches.

8. **Nonlinear Optical Directional Couplers:**
    - Nonlinear optical directional couplers use the Kerr effect, where the refractive index of a material changes with optical intensity, to control light propagation. These devices are used in all-optical switches and signal-processing applications.

9. **Hybrid Directional Couplers:**
    - Hybrid directional couplers combine multiple materials or technologies to achieve specific coupling characteristics or to address particular application requirements. For example, a hybrid coupler may combine silicon photonics with a lithium niobate phase modulator for advanced modulation.

The choice of the optical directional coupler category depends on the application's requirements, including the desired coupling ratio, wavelength range, and compactness. Different categories of couplers offer different advantages and trade-offs, and they are selected based on the unique needs of the optical system or network they are being used in.

2.5 Types of PDCs in Use

Optical directional couplers come in several variations, each designed to suit specific applications and performance requirements.Some of the common types of optical directional couplers include:

Y-Junction Directional Coupler:

A Y-junction coupler is a simple design in which one waveguide splits into two separate waveguides. It is often used as a basic power splitter.

Tapered Directional Coupler:

Tapered directional couplers are designed with gradual changes in waveguide dimensions to achieve the desired power coupling. They can be used for various applications, including power splitting and coupling between different waveguide sizes.

Multimode Interference (MMI) Coupler:

MMI couplers utilize multimode interference to split or combine light. They are often used in wavelength-division multiplexing (WDM) systems and can achieve relatively uniform power splitting across a wide bandwidth.

Evanescent Coupler:

In an evanescent directional coupler, light is transferred between waveguides through the evanescent field, which extends into the adjacent waveguide. These couplers are suitable for applications where the gap between waveguides is too small for direct coupling, such as in photonic integrated circuits (PICs).

Tunable Coupler:

Some directional couplers incorporate tuning elements, such as phase shifters or heaters, to change the coupling ratio dynamically. These tunable couplers are useful in reconfigurable photonic devices and switches.

Balanced Directional Coupler:

A balanced directional coupler is designed to achieve a specific splitting ratio, often 50:50, by carefully controlling the waveguide dimensions and separation. These couplers are commonly used in interferometers and balanced photodetectors.

Asymmetric Directional Coupler:

Asymmetric directional couplers have waveguides with different dimensions or materials, leading to unequal power splitting. They are employed in various applications, such as mode converters and polarization controllers.

Waveguide Grating Coupler:

Grating couplers use periodic structures to couple light between waveguides and free space or between waveguides and optical fibers. They are often used for on-chip fiber coupling and light in/out-coupling.

Bragg Grating Coupler:

Bragg grating couplers use grating structures to reflect or couple specific wavelengths of light within the waveguide. They are integral to applications like wavelength-selective filters and resonators.

Mach-Zehnder Interferometer:

While not a traditional directional coupler, the Mach-Zehnder interferometer is a device that incorporates directional couplers to create interference patterns. They are used in various optical signal processing applications, such as modulators and demodulators.
The choice of directional coupler type depends on the specific application, such as power splitting, wavelength manipulation, switching, or modulation. Engineers and researchers select the most suitable type of directional coupler based on factors like the desired performance characteristics, bandwidth, and the technology used in the photonic system.

2.6 Functions and Applications of PDCs

Optical directional couplers are used in a wide range of applications in the field of photonics and optical communications. They are essential components for manipulating and controlling optical signals. Here are some common applications where optical directional couplers are used:

Power Splitting and Combining:

One of the most common applications of optical directional couplers is to split an incoming optical signal into two or more output signals or to combine multiple input signals into a single output. This is particularly useful in passive optical networks (PONs), where signals need to be distributed to multiple subscribers.

Wavelength Division Multiplexing (WDM):

In WDM systems, multiple optical signals at different wavelengths are combined onto a single optical fiber for transmission. Directional couplers are used to multiplex and demultiplex these signals, allowing for increased data transmission capacity.

Interferometry:

Optical directional couplers are used in interferometers to create interference patterns, which are valuable in various applications such as optical sensors, interferometric measurements, and optical signal processing.

Optical Modulators and Switches:

Directional couplers are integrated into optical modulators and switches to control the flow of optical signals. They can be used to switch between different optical paths or modulate light intensity.

Integrated Photonic Circuits:

Photonic integrated circuits (PICs) incorporate various optical components on a single chip. Directional couplers are used in these circuits to route and manage optical signals in a compact and integrated form.

Fiber Optic Sensors:

Directional couplers are employed in fiber optic sensors to monitor physical parameters like strain, temperature, and pressure. They are often used in structural health monitoring and industrial sensing applications.

Polarization Control:

Some directional couplers are designed to control the polarization of light. These are used in applications where maintaining a specific polarization state is crucial, such as in telecommunications and quantum optics experiments.

Quantum Photonics:

Directional couplers play a significant role in quantum photonics experiments and devices, such as quantum key distribution systems and quantum gates for quantum computing.

Biomedical Imaging:

In optical coherence tomography (OCT) and other biomedical imaging techniques, directional couplers help split optical signals for imaging and analysis.

Optical Amplifiers:

In optical amplifiers, such as erbium-doped fiber amplifiers (EDFAs), directional couplers can extract and monitor a portion of the signal for control and feedback purposes.

On-Chip Light Coupling:

Directional couplers are crucial in integrating optical components on semiconductor chips, enabling efficient light coupling between different waveguides and components in photonic integrated circuits.

Quantum Photonics:

In the realm of quantum photonics, directional couplers play a role in various applications, including quantum key distribution systems and quantum gates for quantum computing.

The use of optical directional couplers is diverse and continues to expand as the field of photonics and optical communication evolves, enabling the development of advanced and compact optical systems with various functionalities.

Chapter 3

Design Comparisons of Flagship Photonic Directional Couplers in the Wavelength Range of 1310-2000nm

3.1 Literature Study and Secondary Research

3.1.1 My Literature Search Process:

Research Methodology Flowchart:

The flowchart outlines a comprehensive, systematized literature review approach developed and adopted for this research project on [thesis topic], focusing on peer-reviewed articles published after 2010. The sequential methodology, moving from a comprehensive initial literature search to an increasingly narrow, targeted analysis of the most pertinent papers, enabled an efficient synthesis while ensuring the breadth and rigor expected of a scholarly literature review. I first built an inventory of keywords that I would use to search for research publications, conference papers, and specialist reference books written after 2010 by experts in the optical electronics space.

This inventory included the terms:

Silicon photonics; Optical fibers; Silicon Strip; Types of Optical Multiplexers; MZI Couplers; MMI Couplers; Y-Junction Couplers; WDM diplexer; WDM; Multiplexer/demultiplexer; diplexing; Silicon-on-insulator (SOI); Integrated photonics; Optical multiplexer/demultiplexer; 1310/1550 multiplexer/demultiplexer; Waveguide grating; Bragg grating; Photonic integrated circuit; Coupler; High efficiency optical

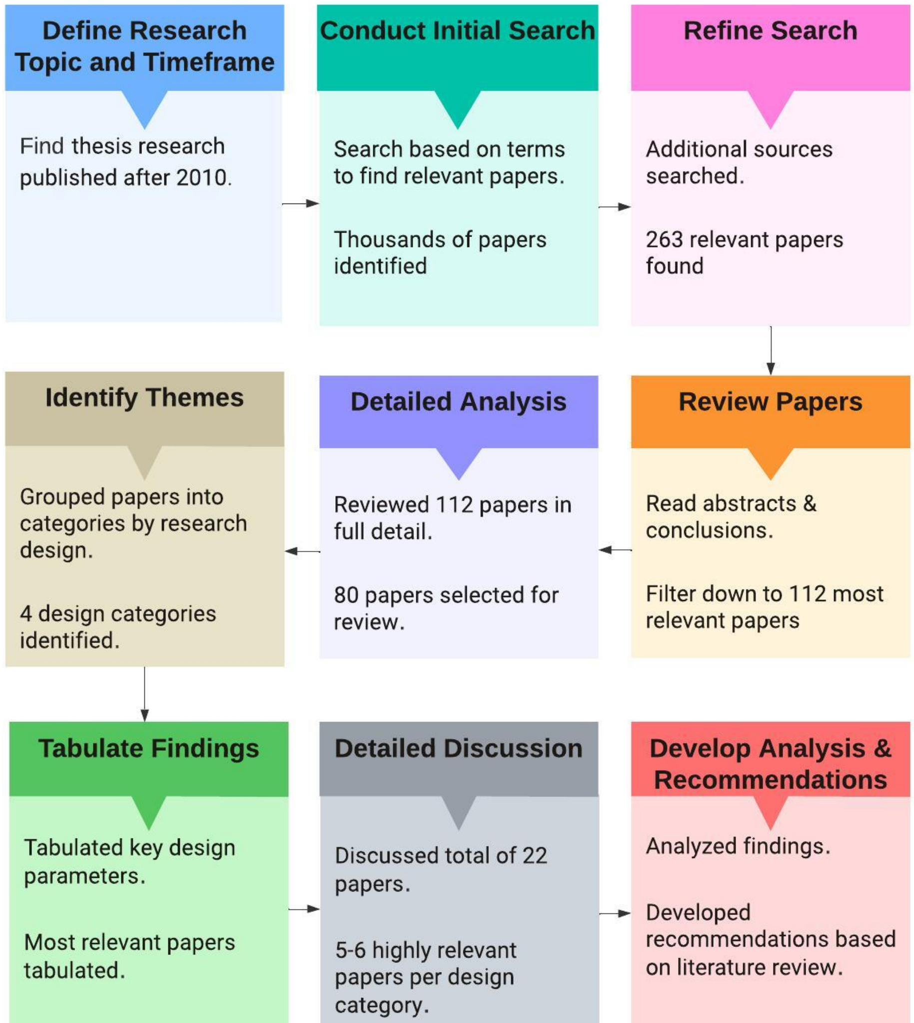

Figure 3.1: Research Process Flowchart

couplers; High extinction ratio; Loss; Silicon grating coupler; Cladding; O band/C band; Beam splitter; Directional grating; Cladding; O band/C band; Beam splitter; Braggs Directional grating

Next, I decided on the publications and research platforms I would consult to gather information and data on the general concepts, principles, design, and performance of photonic devices and directional couplers. I have referenced conference papers and research articles published in refereed journals or conferences on various types or implementations of PDCs like diplexers, MMI couplers, Y-Junction couplers, and Mach Zedner devices. I have also referred to textbooks and reference books that carry established knowledge on photonic devices and photonic directional couplers.

While text and reference books have been my primary source of information for content in chapters 1 and 2, research and conference papers have fed and informed the content of Chapter 3. While these papers are discussed individually in the chapter in the context of the PDC devices they feature, the list of the papers appears in Annexure 1.0 toward the end of this report. Occasionally, I have also drawn from discussions on blogs of scientific and electronics engineering communities like IEEE. More specifically, I probed the following more thoroughly:

Optical Society of America (OSA)

I restricted my search to Optics Express, Optics Letters, Applied Optics, Journal of the Optical Society of America A and B, Optica, and Optics Continuum.

IEEE Xplore Digital Library:

I particularly focused on journals from the IEEE Photonics Society: Photonics Technology Letter, Photonics Journal, Journal of Lightwave Technology, Journal of Quantum Electronics, and Journal of Selected Topics in Quantum Electronics.

SPIE Digital Library:

I searched for papers in the journal Optical Engineering.

Conferences

I also referred to Conference proceedings to search for relevant papers. The conferences of interest were:

- IEEE Photonics Conference
- IEEE Group IV Photonics Conference
- Conference on Optical Fiber Communications
- Conference on Lasers and Electro-Optics
- Conference on Lasers and Electro-Optics Europe
- Conference on Lasers and Electro-Optics Pacific Rim

- European Conference on Optical Communications
- European Conference on Integrated Optics
- Integrated Photonics Research, Silicon and Nanophotonics (recently this is part of the Optica Advanced Photonics Congress)
- Optoelectronics and Communications Conference
- Asia Communications and Photonics Conference
- SPIE Photonics West OPTO

Next, I filtered all the papers from the above sources published after 2010 using the two dozen and odd keywords I listed above. The search threw up thousands of results. I invested more than two weeks reading through the abstracts and conclusions and shortlisted 212 papers for deeper review. In the next round, I sorted papers by their coverage of both design parameters and performance metrics. Eventually, I allowed only 75 papers to enter my studies. In this thesis dissertation, I have avoided discussing every paper or detailing devices or the research results the researchers reported. I have written about the devices to the extent it was necessary to explain the four design parameters that I considered – Length, Gap, Width, and Bandwidth; and four performance metrics – Extinction Ratio; Insertion Loss; Figure of Merit (FOM1), and FOM. I have presented my comparison findings and analysis in a table that looks like this:

Design	Exp/ Theory	λ_1-λ_2(nm)	L (µm)	W$_d$ (µm)	Gap (nm)	ER (dB)	IL (dB)	FOM1	FOM (µm)

Table 3.1: Reference Data table structure

Table 3.1 is the reference structure. In this, the Design column cites the reference paper.The next column indicates if the given paper demonstrates experimental measurements or theoretical simulations and modeling.λ_1, and λ_2 shows the overall wavelength range of operation in nanometers (nm). Critical device dimensions are also listed, including L - the total length in microns, W_d - the waveguide width, and Gap - the distance between coupled waveguides within the photonic circuit highlighted for its precision on the nanoscale order. Performance metrics quantified comprise the Extinction

Ratio (ER) representing modulation depth and optical loss defined via Insertion Loss (IL). Higher ER and lower IL are desired. Figures of Merit FOM1, FOM incorporate these modulation efficiency metrics to allow standardized comparison between device demonstrations, with higher values indicating better combined performance.

Where,

$$FOM1 = ER/IL \tag{3.1}$$

it has no units.

$$FOM = \delta\lambda * FOM1 \tag{3.2}$$

where, $\lambda_1 - \lambda_2 = \delta\lambda$,units-micro meters(µm)

The papers I have referenced cover diplexers, MMI, MZI, and Y-junction devices. These papers feature unique implementations of novel waveguide designs, structures, and materials to achieve varying performance results related primarily to wavelength division multiplexing and mode multiplexing.

In the seven books I consulted in this thesis project, I have studied and explored established Physics and engineering concepts, principles, models, and design of photonic devices in general and those underlying PDC. I have also studied these books to develop a classification and the typology of photonic directional couplers, which I present in Chapter 2. I consulted the following texts:

1. David L. Andrews; Photonics: Scientific Foundations, Technology, and Applications, Volume 1: Fundamentals of Photonics and Physics; Published 2015
2. Leila Abdolahi; Graphene-Silicon Photonic Integrated Circuits: Design, Technology and Devices. Published 2017
3. John P. Dakin & Robert G. W. Brown; Handbook of Optoelectronics, Second Edition Volume 2: Enabling Technologies; Published 2017
4. Lukas Chrostowski & Michael Hochberg; Silicon Photonics Design: From Devices to Systems; Published 2015
5. Bahram Jalali, Silicon Photonics; Published 2014
6. Ohtsu & Motoichi; Handbook of Nano-optics and Nanophotonics; Published 2013
7. Shun Lien Chuang; Physics of Photonic Devices; Published 2009

3.2 Analysis & Reporting

Primarily, my focus in this thesis is to study and compare the coupling performances of multiplexers and couplers carrying different designs. I use ER and IL as the main performance metrics to evaluate various coupler models, and variants innovated since 2010, about which I gathered information from the papers I reviewed.The designs of high-extinction ratio and low-insertion loss couplers receive the main attention for obvious reasons. i.e., 3.1 – and hence coupling designers must attempt to maximise FOM1 Next 3.2 The goal is to achieve the highest possible Figure of Merit (FOM), where FOM1 should be maximized to increase the maximum value of FOM. The multiplication of these two factors should result in the overall maximum value having units in µm.

I tabulate the FOM 1 and FOM values for all featured optical couplers – Y-Junction; MMI and, MZI and FoM values to arrive at a performance value. Finally, I arrive at some conclusions on what may be the ideal dimensions for achieving a perfect design for each part of optical couplers.

3.3 Critical Considerations In Optical Directional Couplers Designing

Photonic directional couplers are proposed for multiplying input optical signals or merging several into one unified signal. Their design, therefore, essentially includes arranging integral elements like ports, waveguides, and controllers shown in Fig.3.2 [36]in a manner that allows for, steers and controls the transfer of optical power between waveguides.

3.3.1 Conceptual & Theoretical Considerations

Operating Wavelength Consideration:

Keeping the wavelength range uppermost in mind is the most basic of considerations of directional coupler design. The specific wavelength or range of wavelengths on which a coupler is expected to operate varies across use cases and applications. The choice of material and waveguide dimensions depend decisively on the wavelengths of interest or their range.

Coupling Coefficient:

The coupling coefficient determines the strength of the interaction between the two waveguides.A higher coupling coefficient results in more efficient power transfer.It depends on factors like the waveguide separation and the effective refractive index difference between the waveguides.

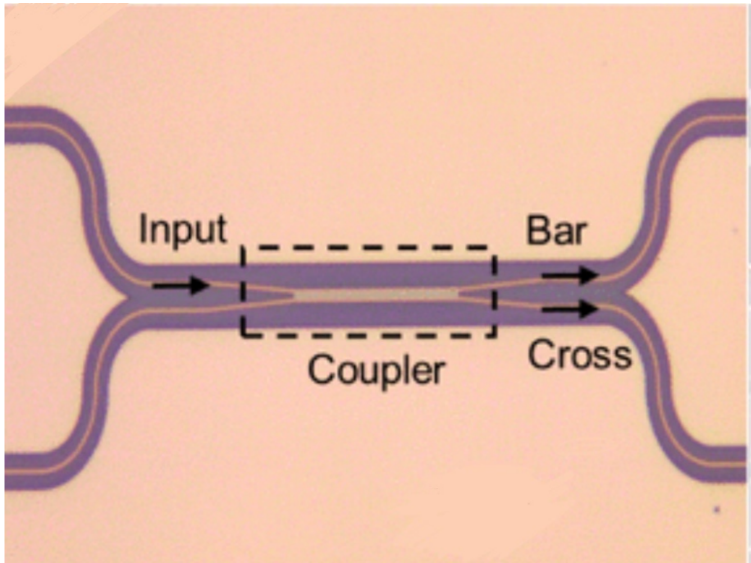

Figure 3.2: Design Schematic of a Directional Coupler [25].

Evanescent Coupling:

In many directional couplers, power is transferred between waveguides through the evanescent field, which extends into the adjacent waveguide.Understanding evanescent coupling and its dependence on the gap size and wavelength is critical for optimizing coupler performance.

Effective Refractive Index:

The effective refractive index of the waveguides depends on the mode profiles and can be influenced by factors like the wavelength of light. It plays a central role in determining the coupling length and the power transfer characteristics.

Power Splitting Ratio:

The power splitting ratio of a directional coupler refers to the proportion of the input power transferred to each output waveguide. This ratio is typically determined by the design and parameters of the coupler and is essential for applications like power splitters and couplers.

Phase Matching:

Achieving phase matching is crucial in applications where the relative phase between the output waveguides is important, such as interferometers.Phase matching ensures constructive or destructive interference as required.

Nonlinear Effects:

At high optical power levels, nonlinear effects can influence the behavior of directional couplers. Understanding these effects and their impact on performance is important for high-power applications.

Polarization Sensitivity:

Some directional couplers are sensitive to the polarization of the incoming light. This property can be advantageous in applications like polarization controllers but needs to be carefully considered in other cases.

3.3.2 Grating Considerations

Gratings play a crucial role in photonic directional couplers by helping to control light coupling between waveguides. Photonic directional couplers are fundamental components in integrated photonics, used for various applications like wavelength division multiplexing, beam splitting, and optical switching. Gratings enhance the functionality and performance of directional couplers in several ways [37]:

Wavelength Selectivity:

Gratings are designed to have a specific period or pitch corresponding to a particular wavelength or range of wavelengths. By adjusting the grating period, you can selectively couple light of a specific wavelength, allowing for wavelength-dependent functionality in photonic circuits. This is especially useful in wavelength division multiplexing (WDM) systems, where different wavelengths must be separated or combined.

Mode Conversion:

Gratings can convert the mode of light propagating in a waveguide. For example, a grating can convert a fundamental mode (TE0 or TM0) to a higher-order mode (TE1 or TM1) or vice versa. This can be useful for mode multiplexing and demultiplexing applications.

Coupling Efficiency:

Gratings enable efficient light coupling between waveguides with different modes or core sizes. The grating structure can be optimized to maximize the coupling efficiency, reducing optical losses in the coupler. This is particularly important in photonic devices where minimizing losses is critical.

Polarization Control:

Gratings can be designed to couple light of specific polarizations, making them valuable in polarization-dependent devices or applications where polarization control is needed.

Tunable Coupling:

Gratings can be designed to provide tunable coupling between waveguides. By changing the period or other grating parameters, you can dynamically control the coupling strength, which is beneficial for reconfigurable photonic circuits and devices.

Compact Design:

Gratings are compact components, allowing for the miniaturization of photonic directional couplers. This is important in integrated photonics, where space constraints are common.

Low Crosstalk:

Well-designed gratings can minimize crosstalk between waveguides, ensuring that light is efficiently coupled to the desired output channel while avoiding interference with other channels.

Filtering:

Gratings can serve as filters by selectively transmitting or reflecting certain wavelengths of light. This can be employed in various applications, such as signal filtering and spectral analysis.

Customized Functionality:

Gratings are highly versatile and can be engineered to provide custom functionalities in photonic directional couplers, depending on the application's specific requirements.

In summary, gratings are essential in photonic directional couplers because they enable precise control over light coupling between waveguides, making these devices versatile and adaptable for a wide range of optical applications in integrated photonics and telecommunications.

3.3.3 Bragg Grating

A Bragg Grating (BG) [38] is a periodic structure or pattern of alternating high and low refractive index regions in an optical fiber or waveguide.This periodicity creates a wavelength-selective mirror, allowing the BG to reflect specific wavelengths of light while allowing others to pass through.Bragg Gratings are crucial components in optical communications, sensing, and filtering applications.Here are the key features and applications of Bragg Gratings:

Periodic Structure:

A Bragg Grating typically comprises a series of equally spaced, alternating high and low refractive index regions. This periodicity gives rise to a wavelength-dependent interference phenomenon that selectively reflects certain wavelengths of light.

Wavelength Selectivity:

Bragg Gratings act as wavelength filters, reflecting a narrow band of wavelengths that satisfy the Bragg condition. The Bragg condition is given by the equation:

$$n\lambda = 2\Lambda \tag{3.3}$$

where:
- n is the effective refractive index of the optical waveguide.
- λ is the wavelength of light.
- Λ is the period of the grating structure.

Only wavelengths that meet this condition are efficiently reflected by the grating.

Fabrication Techniques:

Bragg Gratings can be created using various techniques, including UV exposure, phase masks, and interference lithography. These techniques create periodic changes in the fiber's refractive index or waveguide.

Applications:

• Wavelength Division Multiplexing (WDM): Bragg Gratings are used to separate and combine different wavelengths of light in optical communication systems. This is crucial for multiplexing and demultiplexing signals on optical fibers, enabling the transmission of multiple data channels on a single optical fiber.
• Sensors: Bragg Gratings are employed in various sensing applications. Changes in temperature, strain, pressure, or the surrounding environment can alter the grating's periodicity, causing a shift in the reflected wavelength.This shift measures physical parameters, making Bragg Gratings useful in structural health monitoring, the oil and gas industry, and environmental monitoring.
• Fiber Lasers and Amplifiers: Bragg Gratings are used in fiber lasers and amplifiers to provide wavelength stability and selectivity. They act as cavity mirrors that allow the laser to oscillate at specific wavelengths.
• Dispersion Compensation: Bragg Gratings compensate for dispersion in optical communication systems, ensuring that different wavelengths travel at the same speed, reducing signal distortion.

Types of Bragg Gratings:

• Uniform Bragg Grating: A grating with a constant period throughout.
• Chirped Bragg Grating: The period varies along the length of the grating, which allows for dispersion compensation in optical systems.
• Tilted Fiber Bragg Grating (TFBG): These gratings are tilted relative to the fiber's axis, providing a broader angular reflection spectrum.

Fiber Type:

Bragg Gratings can be inscribed in various optical fibers, including single-mode, polarization-maintaining, and photosensitive, depending on the application.

Bragg Gratings is critical in photonics and optical communications by enabling wavelength-selective filtering, dispersion management, and sensing capabilities.Their versatility and tunability make them valuable tools in various applications.

3.3.4 Practical Designing Considerations

Input and Output Ports:

The input port feeds the incoming optical signal (or signals) to the input waveguide at the time of launch, and the output port channels the output optical signal fed to it by the output waveguide at the time of signal exit. The input and output ports must be synced well for efficient optical coupling results.

Optical Waveguides Material & Design:

Optical waveguides are contraptions designed to trap optical signals and manipulate their energies by splitting or merging them. Photonic directional couplers are typically made up of at least two optical waveguides - one input and another output - constructed out of silicon, silica, or other optical materials and designed to confine and guide optical signals or light within a small cross-sectional area. The dimensions and properties of the waveguides - like refractive index, core size, and geometry - are critical determinants of the performance of directional couplers.

Waveguide Fabrication:

The precision and quality of waveguide fabrication techniques, such as lithography and etching, significantly impact the performance of directional couplers. Accurate fabrication is essential for achieving desired coupling characteristics.

Coupling Zone Management:

This is effectively the playground or action zone of a directional coupler where the input and output waveguides interface and collaborate to split or merge optical signals. Essentially, this is where optical signals from the input source are transferred to the output waveguide for manipulation and processing. This zone or region is the heart of a typical directional coupler, as the waveguides are barely microns apart, and this separation must be precisely managed to ensure optimal coupling performance.

Design Parameters:

The dimensions, size, and shape of the waveguides; the separation among them in the coupling region, and the refractive index contrast between the core and the cladding are some of the mission-critical design parameters considered while designing directional couplers, including the optical or photonic ones. These parameters typically impact the optimality of coupling efficiency, power splitting ratios, and bandwidth fidelity.

Waveguide Mode Profiles:

The electromagnetic fields of the modes in the waveguides of a coupler interact with each other, enabling power transfer between them. This can happen only when these modes of the waveguides overlap with one another in an optimal manner in the coupling region. The overlap of the waveguide mode profiles is determined by the geometry of the waveguides and their refractive index contrast.

Dynamic Control Elements:

Many tunable or switchable devices need decouplers whose strengths must be variable. This dynamic control of the coupling ratio is achieved by changing the effective refractive index of one of the waveguides by using electrode heaters, phase shifters, or other control mechanisms.
These elements form the foundation for the design, analysis, and application of photonic directional couplers. Engineers and researchers must consider these factors to optimize coupler performance for various applications in photonics and optical communication systems. Their design and performance depend on precisely controlling the above elements to achieve the desired optical functionality.

3.4 Review of Some Emergent Designs of Photonic Multiplexers

3.4.1 On-Chip Silicon Triplexer Asymmetrical Directional Based on Couplers [1]

Fiber To The Home (FTTH) has been developing rapidly recently. The triplexer is one of the critical components in the FTTH system, which is used to process signals at three wavelength channels: 1.31µm for uploading, 1.49 µm for downloading, and 1.55 µm for video broadcasting. The researchers Hongnan Xu and Yaocheng Shi demonstrate in this paper [1] an on-chip silicon triplexer with a high performance and compact footprint; the asymmetrical directional couplers (ADCs) are used as wavelength filters in the proposed triplexer. The three wavelengths are separated and coupled into different output ports by carefully designing the phase mismatch and coupling strength for each asymmetrical directional coupler. The measured excess losses are less than 1 dB for all the three channels. The 3-dB bandwidths are 70, 30, and 20 nm for the three output ports (1.31, 1.49, and 1.55 µm), respectively. The total length of this ADC-based triplexer is 150 µm.

The authors have studied numerous triplexers, including the ones using the thin film filters, the diffraction gratings, and the planar lightwave circuits (PLCs), and have concluded that PLC-based triplexers offer advantages due to the easy fabrication, low cost, and small footprint. However, the triplexers based on the AWGs and PhCs show small footprints and high extinction ratios but suffer from the relatively narrow bandwidth, especially for the 1.31µm wavelength band. On the other hand, the MMI- and DC-based triplexers have relatively large bandwidth.

The parameters for the proposed triplexer are summarized as follows: W0,1 = 325 nm, W1,1 = 691 nm, W0,2 = 350 nm, W1,2 = 742 nm, W0,3 = 275 nm, W1,3 = 584 nm, Wg,1 = 400 nm, Wg,2 = 300 nm, Wg,3 = 125 nm, Lc,1 = 34.20µm, Lc,2 = 15.70 µm and Lc,3 = 2.87 µm. The total length of the triplexer is approximately 150µm. The light propagation profiles and transmittance spectra are computed for the triplexer using the 3D FDTD method for three cascaded ADCs. The 1.49-µm and 1.31-µm light go directly across the first ADC and third ADC and output from O1 and O3, respectively. Part of the 1.55-µm light is coupled into the first filter but goes back into the single-mode waveguide and then filtered out by the second ADC.

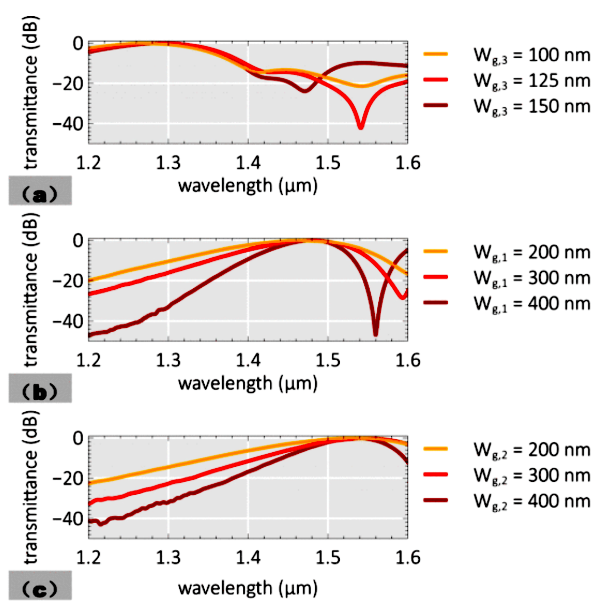

Figure 3.3: Triplexing Responses(a),(b),(c) across different wavelength range [1].

Analysis:

- The crosstalk levels are measured to be -27.07 dB, -23.03 dB, and -25.84 dB for the 1.31 µm, 1.49 µm, and 1.55 µm wavelengths, respectively. Low crosstalk is crucial for the efficient functioning of FTTH systems.

- The total length of the triplexer is approximately 150 µm, making it relatively compact. This is beneficial for integration into FTTH systems where space may be limited.

- The proposed triplexer requires only one step etching, indicating an easy fabrication process. This simplicity in fabrication can contribute to cost-effectiveness.

- The use of SOI technology with a 220-nm thick silicon top layer and a 2-µm thick oxide buffer layer provides a suitable platform for efficient light propagation.

- The performance of the ADC-based triplexer is influenced by wavelength sensitivity. The narrow bandwidths for ADC1 and ADC2 are attributed to incomplete light coupling when the wavelength deviates from the band center.

- The measured 3-dB bandwidths are slightly narrower than the simulation results due to the deviation of waveguide widths from optimized values during fabrication.

- The proposed triplexer works only at the TE polarization state due to the birefringence in the silicon nanowire waveguide. This limitation might require additional measures to reduce polarization dependence in specific applications.

3.4.2 Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits [2]

Driven mainly by the high refractive-index contrast of the waveguide structure and CMOS-compatible fabrication technology, high-density integration and mass production of devices have become possible thanks to Silicon-on-insulator (SOI) emerging as a promising platform for photonic circuits. However, this high index contrast also induces a large polarization-dependent dispersion or loss for standard components. It makes SOI inconvenient to integrate with other polarization-insensitive platforms, like optical fiber networks. A polarization diversity scheme could be employed instead of pursuing complex polarization-independent devices on SOI.

Liu Liu, Yunhong Ding, Kresten Yvind, and Jørn M. Hvam, the authors of this paper [2], propose a polarization converter design on SOI to be concise and effective. It works by utilizing cross-polarization coupling between two waveguides made of SOI material with different widths. Compared to other polarization converters, this structure can be fabricated with ordinary deeply-etched SOI wire devices and waveguides, thus requiring no additional fabrication steps. A polarization splitting and rotating device has been developed by researchers for use in the interface section of a polarization diversity circuit.The device is compact, with a few tens of microns length. It is also simple, having only two parallel silicon-on-insulator wire waveguides with different widths eliminates the need for additional and nonstandard fabrication steps. Experimental results show a total insertion loss of 0.6dB and an extinction ratio of 12dB across the entire C-band. In this case, the orthogonal polarization contents of the input light are first divided into two different waveguides using a polarization splitter.To simplify the processing on the remaining part of the photonic chip, a polarization rotator is used in one of the waveguides to rotate the polarization by 90°.As a result, only one polarization needs to be dealt with. An identical set of polarization rotators and splitter can combine the two polarizations without any interference at the output. The structure of the PSR device is sketched in

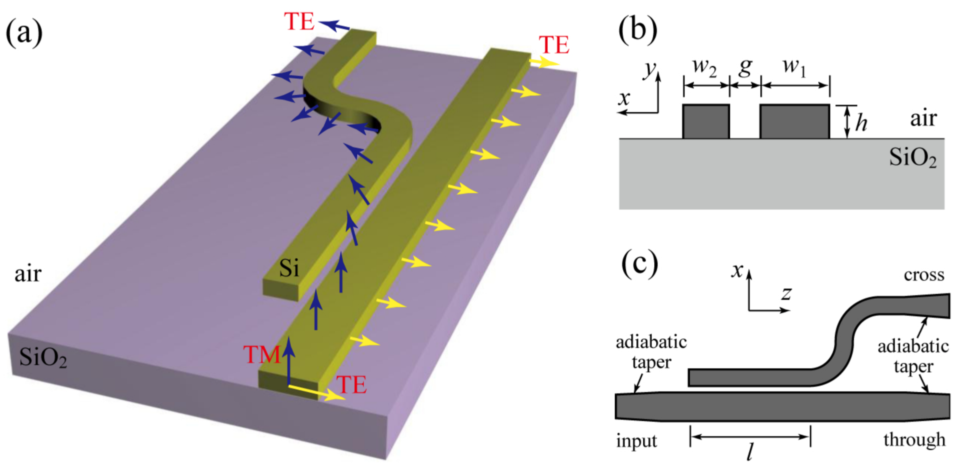

Figure 3.4: The Structure of SOI Polarization Splitting & Rotating device (a) three-dimensional model; (b) x-y cross-section; (c) x-z cross-section [2].

Fig.3.4. It has two parallel SOI photonic wire waveguides coupled to each other. To achieve cross-polarisation efficiently, top cladding is employed with the air. The widths (w1 and w2) of both the waveguides (waveguide one and waveguide 2, respectively) are modified so that the effective index of the fundamental transverse-magnetic (TM) mode in waveguide 1 is equal to that of the fundamental transverse-electric (TE) mode in waveguide 2. Here, we choose w1 = 600 nm and w2 = 333 nm. The height of the silicon waveguide layer used in the experiments is 250 nm, as specified by the chosen SOI wafer parameter.

Additionally, at the selected widths, the effective index (TE mode) of the TE mode in Waveguide 1 is significantly different from that of any guided mode in Waveguide 2. As a result, the coupling mode theory suggests that the TE mode in waveguide 1 can freely pass through the device. Generally, the structure depicted in Fig. 3.4 has the capability to couple the TM mode from the input waveguide to the other waveguide and convert it into a TE mode, all while leaving the TE mode in the input waveguide unaffected.

Analysis:

- FOM 1=20 calculated using ER and IL, which is a good value, but when FOM using bandwidth was calculated as 2µm simultaneously used as polarisation splitter and rotator.

- The device is compact, with a total length of tens of microns, making it suitable for integrating into photonic circuits.

- The device is built on the silicon-on-insulator (SOI) platform, which is CMOS-compatible, allowing for high-density integration and mass production of devices.

- The device consists of only two parallel SOI wire waveguides with different widths, requiring no additional and nonstandard fabrication steps.

- The high refractive-index contrast of the waveguide structure in SOI can induce polarization-dependent dispersion or loss for normal components, making integrating with other polarization-insensitive platforms inconvenient.

- While the device itself is simple, the fabrication process involves E-beam lithography and dry etching technologies, which may add complexity to the manufacturing process.

3.4.3 Design and Demonstration of Compact and Broadband Wavelength Demultiplexer Based on Subwavelength Grating (SWG) [3]

As we know, technology for separating and combining different wavelengths is fundamental to the WDM system. Integrated wavelength division demultiplexer is essential for building broadband services for Big data, extensive capacity communication, and cloud computing applications due to its device size and performance advantages.In this context, demultiplexing wavelengths of 1310/1550 nm have become very important. Conventional wavelength demultiplexers, such as diffraction-grating couplers and micro-ring resonators, exhibit small footprints and high extinction ratios, but their bandwidths are much narrower. By comparison, multimode interference (MMI) devices provide relatively broad optical bandwidth and relaxed fabrication tolerance.However, they usually have a relatively large length. In this paper [3], the authors Fuling Wang, Xiao Xu, Chen Zhang, Chonglei

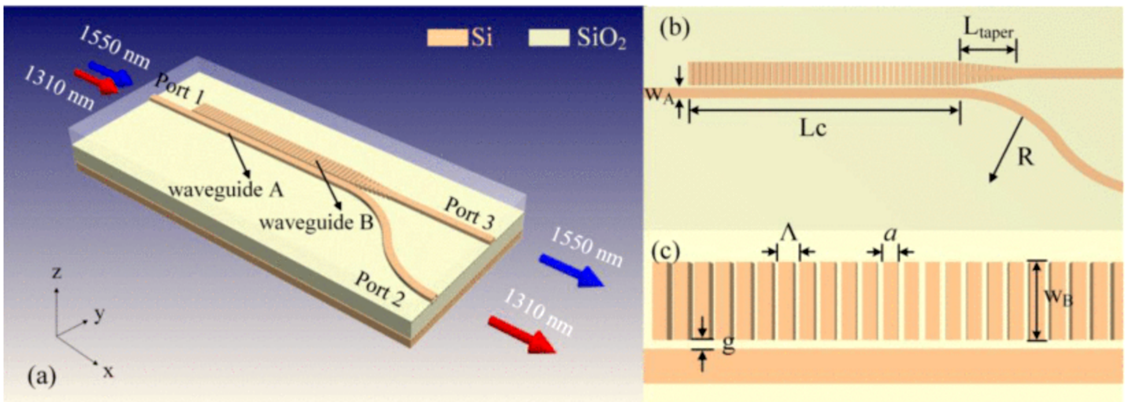

Figure 3.5: (a)3D schematic configuration of the designed wavelength demultiplexer. (b) Top view of the device. (c) Enlarged view of the coupling region [3].

Sun, and Jia Zhao show an ultracompact and broadband 1310/1550 nm wavelength demultiplexer by utilizing SWG-assisted asymmetrical directional coupler. The embedded SWG enables significantly reduced footprint due to the precise phase matching at 1550 nm and significant phase mismatch at 1310 nm. Therefore, the input light at 1310 nm propagates through the port with negligible cross-coupling, while the light at 1550 nm is coupled to the adjacent SWG waveguide within one coupling length, and an ultra-compact footprint with a total length of 9 µm is obtained. The fabricated device displays low insertion losses of less than 1.7 dB at 1310 and 1550 nm and provides high extinction ratios (ERs) of 23 dB and 19 dB at 1310 and 1550 nm, respectively. Its 3-dB bandwidths are 85 nm for 1310 nm (ER≥15 dB) and 140 nm for 1550 nm (ER≥10 dB), which shows a broadband property that can cover almost the whole O-band and C-band. This device is promising for high-efficiency wavelength demultiplexing with a compact footprint and broad bandwidth.

Most demultiplex-ers are assembled with the directional coupler (DC) thanks to its high extinction ratio and easy design process. In this work, the researchers experimentally demonstrate their wavelength demultiplexer design that splits the wavelengths of 1310 nm and 1550 nm on a silicon-on-insulator (SOI) platform. In our design, a SWG waveguide of the DC replaces one strip waveguide. By optimally choosing the structural parameters of the SWG, its effective index is tuned carefully to satisfy the phase-matching condition at 1550 nm. Meanwhile, a significant phase mismatch is maintained at 1310 nm. Therefore, the input light at 1310 nm propagates to the through port with negligible cross-coupling, while the light at 1550 nm is coupled to the adjacent SWG waveguide within one coupling length. Moreover, by employing the SWG configuration, the beat lengths are shortened substantially, reducing the device length. The fabricated device displays low insertion losses of less than 1.7 dB for 1310 and 1550 nm.

Analysis:

- FOM1 was calculated as 11.17, but FOM=2.68µm is not a desired value.
- Proposed wavelength demultiplexer has a total length of 9 µm, making it ultracompact compared to traditional devices, which are typically much longer. This compact size is advantageous
- The device exhibits broadband properties, with 3-dB bandwidths of 85 nm for 1310 nm and 140 nm for 1550 nm. This broad bandwidth is beneficial for accommodating a wide range of wavelengths within the O-band and C-band.
- Incorporation of SWGs reduces the device footprint and helps achieve precise phase matching at 1550 nm and a large phase mismatch at 1310 nm.
- The device's design is based on asymmetrical directional coupling with SWGs, offering an alternative and potentially simpler approach than other demultiplexing technologies.
- The source band limits the 3-dB bandwidth at 1550 nm. This limitation indicates that the characteristics of the light source partially constrain the device's performance.
- Device's performance is affected by the parameters of the subwavelength grating, such as duty ratio and pitch. Balancing these parameters for optimal performance may be challenging.
- There is a notable difference between simulated and experimental results, which may raise concerns about the device's reliability and reproducibility in practical applications.

3.4.4 High-Contrast and Compact Integrated Wavelength Diplexer Based on Subwavelength Grating Anisotropic Metamaterial for 1550/2000 nm [4]

It is well known that wavelength (de)multiplexers ((de)WMUXs) are the essential building blocks of a WDM system. The ideal devices would show low insertion loss (IL), low crosstalk (CT), high contrast (C), compactness, high robustness, and easy fabrication. In this paper [4], Danfeng Zhu Han Ye Yumin Liu Jing Li and Zhongyuan Yu demonstrate a high-contrast and compact wavelength diplexer for conventional 1550 nm and emerging 2000 nm based on a subwavelength-grating (SWG) coupler.Simulated by the 3D finite-difference time-domain method, the proposed diplexer possesses a shallow insertion loss and a high contrast of 25.24 (31.7) dB at 1550 (2000) nm.The 200 (108) nm operational bandwidth is achieved with contrast over 15 dB and insertion loss below 0.22 dB. The footprint of the diplexer is only 5.27µm × 11.85 µm.The SWG silicon waveguide thoroughly blocks the light propagation around 1550 nm but fully supports 2000 nm (extinction ratio: 43.11 dB). This grating type anisotropic metamaterial efficiently reduces the coupling length and expands the operational bandwidth. Moreover, such a design has scalability by simply tuning the geometrical parameters of SWG.

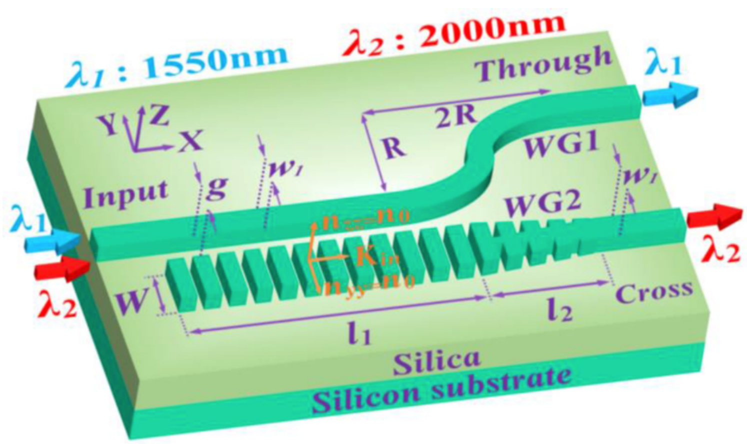

Figure 3.6: Schematic diagram of the wavelength diplexer [4].

The effective grating index in this device equals 2.01 (lower than nBT of 2.94) at 2000 nm. Hence, the grating satisfies the required subwavelength condition. To maintain the phase matching condition, the width of the silicon strip is set as 460 nm (point B). Currently, the effective index of the silicon strip is 2.5 at the wavelength of 1550 nm. Since this grating operates in the subwavelength regime at 1550 nm, it can be regarded as a homogeneous anisotropic material.

Analysis:

- The proposed wavelength diplexer operates over a wide bandwidth, providing flexibility for different applications. Thus, I calculated FOM1=500 and FOM=225µm, which states that it is a good design.
- The design can be scaled for compatibility with other wavelengths by adjusting the structural parameters of the subwavelength grating.
- The diplexer can be integrated into silicon photonic devices, providing opportunities for on-chip applications.
- The diplexer targets the mid-infrared (MIR) range around 2000 nm, tapping into a new telecommunication window with potential applications in biological, chemical, and industrial sensing BUT shows sensitivity to fabrication changes, necessitating careful control during manufacturing.
- The fabrication of the diplexer requires advanced techniques such as electron beam lithography and inductively coupled plasma etching, which may increase the complexity and cost of production.
- Strict phase matching conditions need to be satisfied, and deviations in structural parameters may affect performance, particularly at 2000 nm.
- Although the subwavelength grating design is intended to reduce losses, some losses may still be associated with the grating structure.

3.4.5 Fiber-Chip Bi-Wavelength Multiplexing With Subwavelength Single-Etch Grating Coupler and Diplexer [5]

Silicon photonics has dramatically lowered the cost for optical transceivers due to its high integration density and mass production capability using a matured microelectronics fabrication process. While currently, it is mainly applied in data center interconnect, the access network is another promising application scenario for cost-effective mass deployment. In the passive optical network (PON) [39], in conventional Ethernet PON, upstream and downstream signals are transmitted using wavelength-division-multiplexing (WDM), typically using an O-band near1310 nm and S-band near 1490nm, respectively.

Although it has been successfully implemented using bulk optics, multiplexing on silicon photonic chips and directly interfacing with optical fibers can simplify packaging and significantly reduce costs.

The researchers Lirong Cheng, Simei Mao, Yinghui Wang, and H. Y. Fu propose [5]a

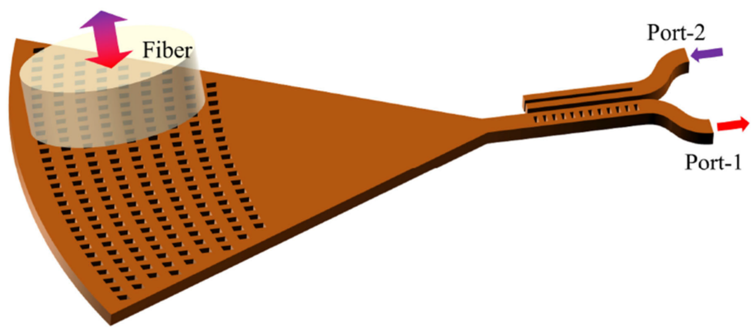

Figure 3.7: Schematic diagram for the proposed subwavelength grating coupler (GC) and diplexer [5].

silicon photonic grating coupling scheme for dual-band multiplexing in optical fibers. A wavelength-polarization diplexer and a dual-band operating grating coupler are designed using subwavelength grating and effective refractive index engineering.On a 220-nm silicon-on-insulator, both devices are fabricated, requiring only one 220-nm complete etch step to facilitate cost-effective production.The subwavelength grating coupler guides S-band and O-band lights from a single-mode fiber into a waveguide as transverse-electric and transverse-magnetic modes, while the subwavelength diplexer separates the two signals into two waveguides. Experimentally, our proposed scheme for coupling and multiplexing can achieve a total insertion loss of –4.26 dB at near 1490 nm and –5.86 dB at near 1310 nm. [39]

Analysis:

- The proposed silicon photonics design allows for efficient dual-band coupling, addressing the challenges of widely separated upstream and downstream wavelengths in passive optical networks (PON).
- The FOM1=37.5 and FOM=6.75µm are calculated using respective parameters, resulting in good performance values.
- The use of SWGs enables practical index engineering, providing a solution to the wavelength sensitivity issue of traditional grating couplers. SWGs also allow for a

single total etch down to the buried oxide (BOX), simplifying fabrication.

- The proposed scheme leverages polarization differences between the two wavelength bands, utilizing transverse electric (TE) for one band and transverse magnetic (TM) for the other. This approach simplifies polarization control for downstream signals.
- The design includes a subwavelength diplexer for efficient multiplexing signals of different wavelengths and polarizations. This enables the simultaneous transmission of signals in O-band and S-band.
- The performance of the fabricated device deviates from simulation results, especially for the O-band coupling at 1310 nm.This discrepancy is attributed to fabrication-induced variations, highlighting the challenges in maintaining precise dimensions during fabrication.
- The design relies on polarization differences between bands.While this can be advantageous for downstream signals, it requires polarization control for input coupling, potentially adding complexity to the overall system.
- The diplexer's performance degrades outside the targeted wavelength ranges, limiting its effectiveness for signals beyond the specified bands.

3.4.6 SWG-based compact broadband two-mode multiplexer on SOI platform [6]

Subwavelength grating (SWG) has attracted much attention in the last decade for its ability to refractive index engineering by altering periodic structures' periods and duty cycles. These periodic structures can be treated as a new homogeneous medium with an equivalent refractive index. The mode-division multiplexer (mode MUX) is an essential building block of an MDM system.Previously, many structures such as asymmetric Y-junctions, counter-tapered couplers, densely packed uniform waveguide arrays, microring resonators, multimode interference couplers, grating-assisted couplers, and asymmetric directional couplers have been used to realize mode MUX. [40]

In this paper [6]Manoranjan Minz, Darpan Mishra, and Ramesh Kumar Sonkar report an SWG-based mode MUX with two-mode channels on the silicon-on-insulator (SOI) platform to operate from 1550 to 1560 nm wavelength range. The device has a coupling region that comprises a subwavelength grating (SWG) waveguide and a conventional multimode strip waveguide. This is a compact two-mode silicon optical multiplexer in which tapers have been employed for adiabatic transition of the fundamental TM modes of the input strip waveguides to the respective fundamental TM modes of the SWG-based waveguide and multimode strip

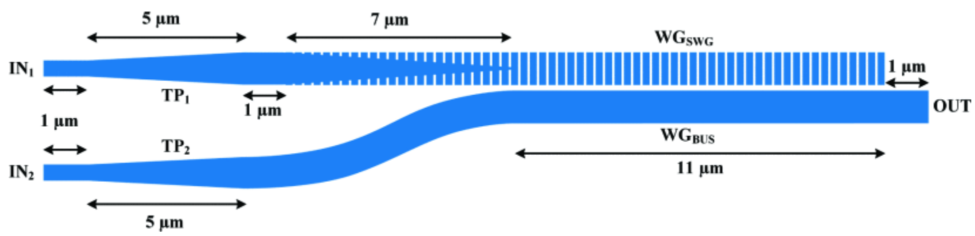

Figure 3.8: Schematic diagram showing the top view of the proposed MUX [6].

waveguide. The duty cycle and grating period are tailored to couple the first-order TM mode of the strip waveguide and the fundamental TM mode of the SWG-based waveguide. A 3D finite-difference time-domain simulation is performed to study the device performance. The multiplexer is very compact with a device length of 26 µm, which exhibits a return loss of $\geq$ 35.62 dB, crosstalk of $\leq$ 33.60 dB, and insertion loss of $\leq$0.29 dB, at 1550 nm.

The top view of the proposed two-mode MUX is depicted in Fig.3.8. The device is designed on the SOI substrate with a 220 nm Si layer sandwiched between an upper and a lower SiO2 layer with 2 m thickness each. The input ports are denoted as IN1 and IN2, and the output port is denoted as OUT. The two input strip waveguides are single-mode waveguides with a width of 500 nm, separated by a distance of 2.65 m. The fundamental TM modes of the input strip waveguides are converted to the fundamental TM modes of the multimode strip waveguides via adiabatic tapers (TP1 and TP2) of length 5µm.

The width of the multimode waveguide is 1µm, which supports two TM modes (fundamental and first-order). For an adiabatic transition between the fundamental TM mode of the multimode strip waveguide and the SWG waveguide (WGSWG), a 7µm taper is used. An S-bend connects TP2 and the multimode waveguide (WGBUS). WGSWG and WGBUS have the same cross-sectional dimension. The distance between WGBUS and WGSWG is kept at 150 nm with a coupling length of 11 µm. The overall length of the device is 26µm. To phase-match the fundamental TM WGSWG mode and first-order TM WGBUS mode, the grating period and duty cycle of WGSWG are taken as 280 nm and 77.5%, respectively.

This device has overcome the limitations of electrical interconnects caused by parasitic capacitances and resistances, which can be overcome by employing optical interconnects. Moreover, the optical interconnects can leverage multiplex-ing schemes, namely, mode-, polarization-, and wavelength-division multiplexing (MDM, PDM, and WDM) to increase the optical link capacity.The data-carrying channels in MDM are the modes of the multimode waveguide, whereas in PDM, transverse magnetic (TM) and transverse electric (TE) modes are the data carriers.In the case of WDM, multiple wavelengths of the same mode can carry distinct data sets.

The grating period of this device is less than half of the wavelength of operation, so the diffraction effect is not observed in the case of SWG-based waveguides. Moreover, the mode fields are delocalized, and the evanescent fields penetrate more into the cladding region, resulting in high coupling strength and low coupling length, thereby achieving compact device size.

The fundamental Bloch-Floquet TM mode of the SWG waveguide is co-directionally coupled to the first-order TM mode of the multimode strip waveguide. The period and duty cycle of the SWG waveguide is varied to match the effective indices of the coupled modes. The 3D finite-difference time-domain (FDTD) numerical technique is implemented for the device simulation and analysis.

Analysis:

- The multiplexer leverages various multiplexing schemes, including mode-division multiplexing (MDM), polarization-division multiplexing (PDM), and wavelength-division multiplexing (WDM). These schemes increase the optical link capacity by utilizing different channels.

- SWG technology allows for refractive index engineering, offering flexibility in designing and optimizing the device.SWG waveguides exhibit high coupling strength, low coupling length, and compact device size.

- The multiplexer is designed to operate in the 1550 to 1560 nm wavelength range, a common range for optical communication applications.

- The simulation results indicate good transmission characteristics with greater than 70% (90%) transmission within the specified wavelength range. The insertion loss (IL), return loss (RL), and crosstalk (XT) are within acceptable limits.

- The paper does not provide information about the power consumption of the proposed device, which is a crucial aspect, especially in the context of modern, energy-efficient optical communication systems.

- The topic and the technology involved might be complex for readers not well-versed in optical communication and waveguide design.

Design	Exp/ Theory	λ_1-λ_2(nm)	L (µm)	W$_d$ (µm)	Gap (nm)	ER (dB)	IL (dB)	FOM1	FOM (µm)
[2]	Exp	1500-1600	36.8	0.6	100	12	0.6	20	2
[3]	Exp	1310-1550	9	0.9	100	$\geq$ 19	1.7	11.17	2.68
[4]	Exp	1550-2000	11.85	0.8	190	$\geq$ 25	$\leq$ 0.05	500	225
[5]	Exp	1310-1490	4.44	0.5	100	$\geq$ 15	$\leq$ 0.4	37.5	6.75
[6]	Sim	1500-1600	26	0.5	150	N/A	$\leq$ 0.29	N/A	N/A
[41]	Sim	1500-1600	25.2	0.5	N/A	30	-1	-30	-3
[42]	Exp	1530-1580	22	0.5	300	$\geq$ 20	1	20	1
[43]	Sim	1550-2000	13.9	0.5	200	30.9	$\leq$ 0.8	38.63	17.38
[44]	Sim	1260-1565	9	0.4	100	$\geq$ 19	$\leq$ 0.2	95	28.97
[45]	Exp	1500-1600	9.5	0.46	N/A	$\geq$ 10	-1.54	-6.49	-0.64
[46]	Exp	1525-1560	55	0.38	N/A	-10.41	-0.79	13.18	0.46
[47]	Exp	1520-1620	15	N/A	N/A	$\geq$ 25	0.04	625	62.5
[48]	Exp	1350-1650	22	0.4	150	2.34	1.34	1.74	0.52
[49]	exp	1536-1544	N/A	0.45	N/A	-27	-5	0.0432	5.4

Table 3.2: Performance comparisons of different Multiplexer designs.

3.4.7 Multiplexer design parameters:

The table 3.2 summarizes key results from recent research papers on Photonic multiplexers. Several performance parameters and device dimensions are reported that help characterize and benchmark the modulators.The first column indicates if the paper presents experimental or simulated data. The operational wavelength range targeted is listed next, covering infrared telecom bands from 1260nm up to 2000nm. Compact microring devices a few tens of micrometers in circumference are demonstrated. The microring width of around half a micron supports single fundamental optical mode propagation & enhances intensity modulation efficiency.The nanoscale gaps between microring & waveguides represent precision silicon photonic fabrication at its finest and help yield high-field intensity overlaps.This leads to large extinction ratios (ER)in [43], signifying deep optical modulation depths above 30dB and super low insertion loss below 0.05dB in [4]. Figures of merit combine these modulation metrics to enable comparison.We notice clear performance trade-offs - achieving ultra-low loss and very high ER simultaneously remains challenging. Some parameters are unreported and are indicated as Not Available(N/A) as values are missing and could not be acquired from reference papers.
Paper [47] has the best FOM1=625, but the final FOM=225µm is high in [4] (as per the calculations done).However, the amalgamation of figures of merit underscores the existence

of clear performance trade-offs, notably in the delicate balance between ultra-low loss and very high ER. This challenge remains a focal point for ongoing research efforts.

3.5 Review of Some Emergent Designs of Y-Junction Couplers

3.5.1 Ultra-broadband 3 dB Power-Splitter: 1.55 to 2 µm Waveband [7]

Wavelength-division multiplexing (WDM) is one of the most promising techniques for large-capacity optical communications and interconnects. Using multiple spectral bands, such as the C + L band technique, is promising to increase the transmission capacity. The researchers Zelu Wang, Yingjie Liu, Zi Wang, Yilin Liu, Jiangbing Du, Qinghai Song, and Ke Xu report in this paper [7] an ultra-broadband and ultra-compact 3 dB power splitter that they have developed. The device combines an adiabatic triple-taper junction with the SWG structure. The junction splits the optical wave equally and smoothly with high efficiency. The SWG is used to tailor the dispersion and suppress the wavelength dependence. This device consists of a triple-tapered junction assisted with SWG waveguides. It is designed on a standard silicon-on-insulator (SOI) substrate with 220 nm top silicon and 2µm buried oxide. Silicon

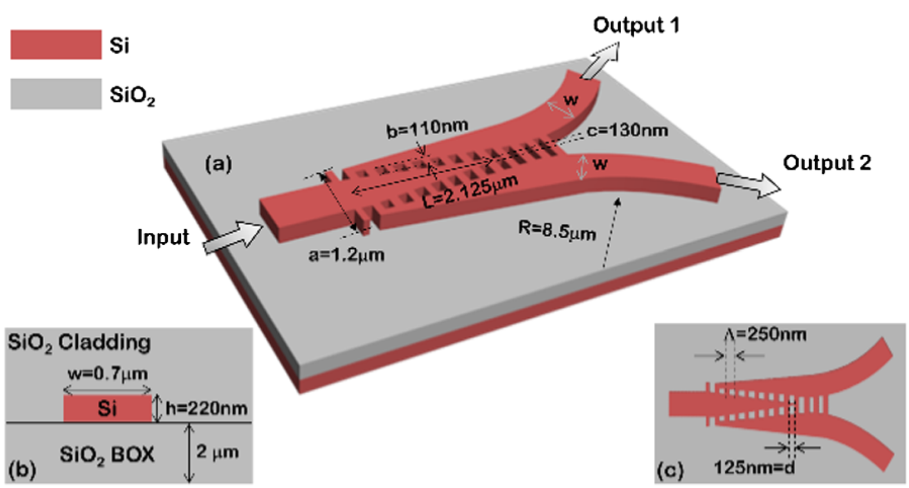

Figure 3.9: (a) Schematic diagram of the designed splitter; (b) cross sec-tion schematic diagram of the silicon waveguide;(c)2D top-view of the device [7].

photonics is a proven device integration technology, and extending the optical communication wavelengths of devices to 2µm can significantly increase data capacity. However, the large waveguide dispersion in silicon creates several challenges. The device reported in this work is an ultra-broadband power splitter on silicon, which has a 0.2 dB bandwidth exceeding 520 nm from 1500 to limitations on the setup and coupling technique. The device insertion loss is below 0.4 dB from 1500 to 1620 nm and 1960 to 2020 nm, respectively. According to these results, the proposed device is believed to operate over broadband from 1.55 µm and 2 µm wavelengths.

Analysis:

- The power splitter demonstrates an ultra-broadband performance, covering wavelengths from 1500 to 2020 nm with a 0.2 dB bandwidth exceeding 520 nm. This is beneficial for applications requiring operation over multiple spectral bands.
- The device has an ultra-compact footprint of only 3 µm $\times$ 2 µm, making it suitable for integration into small-scale photonic circuits. This compact size is advantageous for achieving high integration density.
- The use of a triple tapered junction and subwavelength grating (SWG) structure contributes to the broadband performance of the power splitter. The SWG assists in tailoring dispersion and suppressing wavelength dependence.
- The power ratio between the two output ports is close to unity, and variations are small within the measurement bandwidth, indicating a stable power distribution.
- Fabrication imperfections, such as sidewall roughness, contribute to the backscattering loss, leading to a larger loss than simulation predictions. This may affect the overall device performance.
- The measurement error increases at the edges of the measured wavelength bands due to the limited tuning range of the coupling angles. This could affect the accuracy of the reported performance.

3.5.2 Novel silicon polarization beam splitter at 2 µm [8]

Among various silicon photonic devices, a polarization beam splitter (PBS) is essential in numerous optical systems. Various PBSs have been realized using, e.g., directional couplers (DCs), multimode interferometers, and subwavelength-grating (SWG)-assisted structures. Among them, asymmetric DCs have been popular for their performance excellence and design simplicity. Since most of the PBSs developed in the last 15 years or so have addressed the wavelength band of 1550 nm, there is a need for devices for the wavelength band of 2µm, the increasingly more popular new wavelength window for several applications such as optical fiber communications.

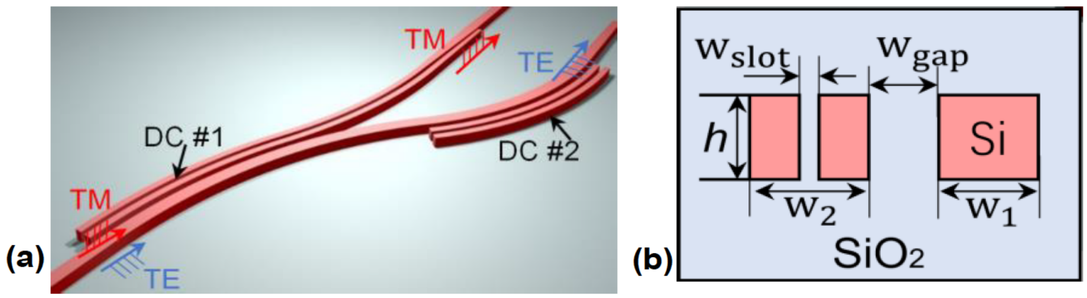

Figure 3.10: Schematic configuration of the proposed PBS. (a) 3D view; (b) side view [8].

In this paper [8], Xinyu Liu and Daoxin Dai demonstrate their silicon polarization-beam-splitter at 2 µm, which they have built using a bent coupler assisted with a nano-slot waveguide that has a high extinction ratio of $\geq$ 15dB and a low loss of $\leq$0.5dB over a broadband. Fig.3.10(a) shows the proposed PBS's three-dimensional view, consisting of two bent DCs in cascade.Each bent DC is designed with a silicon-on-insulator (SOI) strip waveguide and a nano-slot waveguide, as shown in Fig.3.10(b).The TM polarization modes in this structure satisfy the phase-match condition, and cross-coupling happens in DC 1. Finally, the launched TM polarization mode outputs from the cross port. To enhance the bandwidth, bent DC 2 is introduced as a polarizer to remove the uncoupled power of TM polarization in the strip waveguide. For TE polarization, the cross-coupling is depressed significantly because the phase mismatching is enormous, so almost all of the power of the launched TE-polarization outputs from the through port without cross-coupling.

Analysis:

- The proposed polarization beam splitter (PBS) operates in a broad wavelength range of 1825–2020 nm, making it suitable for applications in the 2 µm wavelength band.
- Values of FOM1,FOM are found to be 30,3.3µm respectively using ER,IL,$\delta\lambda$.
- The PBS has a compact footprint of approximately 11 × 48 µm^2, making it suitable for integration into densely packed photonic circuits. This is advantageous for achieving high integration density.

- The fabricated PBS demonstrates good agreement with theoretical expectations, with measured excess losses below 0.5 dB and extinction ratios exceeding 15 dB for both TE and TM polarizations in the wavelength range of 1860-1970 nm.

- The measured performance shows some deviation from theoretical expectations, potentially due to fabrication errors and imperfect filling of the silica upper cladding in the nano-slot region. Further optimization of the fabrication process is suggested for improved performance.

- A blue shift in the central wavelength is observed for TM polarization, partially attributed to fabrication errors. This shift may affect the alignment of the PBS with specific wavelength channels.

3.5.3 Y-branch edge coupler between cleaved single mode fiber and nanoscale waveguide on silicon-on-insulator platform [9]

Edge coupler is one of the most essential input/output (I/O) interfaces to connect photonic integrated circuits and fibers for its low coupling loss, broadband operation, and low polarization dependent loss (PDL). Instead of the traditional inversed taper waveguide and lensed fiber commonly used for low-loss coupling due to their similar mode size for nanoscale waveguides on silicon-on-insulator (SOI) platform, the researchers Xin Tu, Hongyan Fu, and Dongyu Geng use a cleaved mode and a nanoscale silicon waveguide to build this low-loss and alignment-tolerant Y-branch edge coupler. The simulation results show that the optimal structure has a coupling loss of 0.5 dB and 1.0 dB for TE and TM mode, respectively. The alignment tolerances for 3-dB excess loss in the horizontal and vertical directions are over ±3.7Pm and ±3.5Pm for TE mode and ±4.1Pm and ±4.8Pm for TM mode.

This novel method [9]seems suitable not only for characterization in labs but also for mass production due to its high alignment tolerance and ease of packaging. The device is designed to have a two-stage waveguide structure consisting of a thin Y-branch waveguide and a rib taper done on the commercial SOI wafer with 2 3 µm buried oxide (BOX). Since the thin Y-branch waveguide has an effective refractive index and mode size similar to the cleaved SMF, the mode mismatch loss is relatively low. The light from the fiber is first coupled into the super mode at the edge. Then, the optical mode is adiabatically reduced in size with decreasing spacing. Finally, it is gradually transferred into a standard single-mode waveguide with a rib taper. In addition, the silicon substrate in the coupler region is removed and filled with index-matching material, e.g., UV glue OF-143, to eliminate the optical leakage into the substrate. In the model, the refractive indexes of Si and oxide are assumed to be 3.48 and 1.444 at 1547 nm, respectively. The standard SOI waveguide has

220 nm height and 500 nm width. The minimum branch width is 180 nm according to the state of art of 248-line lithography.

Analysis:

- The proposed Y-branch edge coupler exhibits low coupling loss, with simulated values as low as 0.5 dB for TE mode and 1.0 dB for TM mode. This indicates efficient light transmission between the cleaved single-mode fiber and the nanoscale silicon waveguide.
- The simulated transmission spectra show that the coupler maintains low coupling loss (<0.6 dB for TE mode and <1.2 dB for TM mode) over a wide bandwidth, thus suitable for various applications.
- Unlike some existing techniques that involve a silica waveguide as a transition, the proposed coupler eliminates the need for an additional waveguide, simplifying the structure and potentially reducing fabrication complexity.
- The coupling loss for TM mode is slightly higher than that for TE mode, reaching up to 1.0 dB. Achieving more balanced coupling losses for both polarizations could be an area for improvement.
- While the structure demonstrates robustness against process corners, some sensitivity to fabrication parameters is evident. Careful control and monitoring during fabrication are essential for consistent performance.

3.5.4 Efficient edge coupler for higher order mode fiber-to-chip coupling [10]

High-efficiency coupling schemes between optical fiber and photonic integrated circuit (PIC) chips are needed to fully realize the promise of the silicon-on-insulator (SOI) platform in developing compact, low-cost, and power-friendly photonic integrated devices. However, most edge coupling methods focus on the fundamental mode. In this paper [10], Yaxiao Lai, Yu Yu, Songnian Fu, Perry Ping Shum, and Xinliang Zhang report having adopted a mode multiplexing technique instead to develop an efficient edge coupler based on double-tip inverse tapers for the coupling and mapping between LP11 in FMF and TE1 modes in SOI chip.They have discovered the two-petal separation and combination method and demonstrated theoretically the same without any complex design compared to the fundamental mode. In the 130 nm device length design, this edge coupler reports a 3.06 dB coupling loss at 1550 nm with a fluctuation of less than 0.45 dB in the 100 nm range.

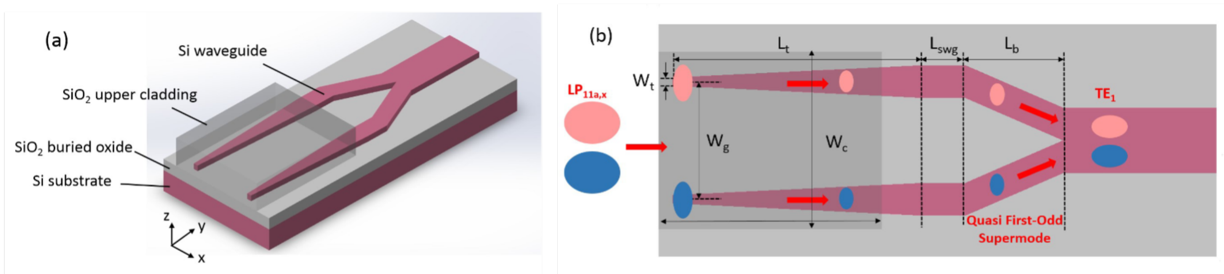

Figure 3.11: Schematics of edge coupler (not in scale) in (a) 3D-view (b) Top view with geometric parameters and transmission symbols [10].

The researchers propose and theoretically demonstrate an efficient edge coupling scheme for first-order linearly polarized mode (LP11) in this work. Their device is a cascade of two identical inverse-tapered channel waveguides and a rib waveguide Y-branch structure to reduce the propagation loss caused by the sidewall roughness in fabrication. The silicon dioxide upper cladding with finite width is decided for better confinement of the mode field that travels in it. A double-tip inverse taper combined with a Y-branch is utilized for the coupling and LP11 to first-order transverse electric (TE1) mode mapping between a cleaved few-mode fiber (FMF) and SOI chip through two-petal separation and combination. The simulated coupling loss at 1550 nm is 3.06 dB with a fluctuation of less than 0.45 dB in the 1500-1600 nm wavelength range.

Analysis:

- The proposed edge coupler is designed for efficient coupling and mapping between the LP11 mode in a few-mode fiber (FMF) and the TE1 mode in a silicon-on-insulator (SOI) chip. The simulation results show a coupling loss of 3.06 dB at 1550 nm, indicating effective mode conversion.

- The simulated transmission spectrum exhibits a low coupling loss with fluctuations less than 0.45 dB in the 1500-1600 nm wavelength range. The coupler maintains good performance over a broad bandwidth.

- The coupler utilizes a symmetric structure with a cascade of two identical inverse-tapered channel waveguides and a rib waveguide Y-branch structure. This symmetry helps maintain a phase difference in the coupled modes, contributing to efficient mode conversion.

- The coupler demonstrates reasonable misalignment tolerance in horizontal and vertical directions. The coupling efficiency degrades by 1 dB within a misalignment range of ±1.5 µm and ±2.5 µm in horizontal and vertical directions, respectively.

- The achieved coupling loss of 3.06 dB at 1550 nm may be considered relatively high for certain applications. Further optimization or the use of lensed FMF could potentially improve this parameter.
- The optimal performance of the coupler depends on several design parameters, such as taper gaps, taper lengths, and Y-branch lengths. Achieving optimal values for these parameters requires careful optimization.

3.5.5 Ultra-broadband Power Splitter using Sub-Wavelength Grating [11]

As the demand for bandwidth increases in optical communications, commonly used optical communication spectra such as C, L, and U bands can no longer satisfy the increasing demand for bandwidth. Ting Yu, Yingjie Liu, and Ke Xu demonstrate in this paper [11]a compact, ultra-broadband power splitter built on a standard silicon photon MPW using a subwavelength grating (SWG) structure, which is operable in the 1.55-µm and 2-µm spectral bands.

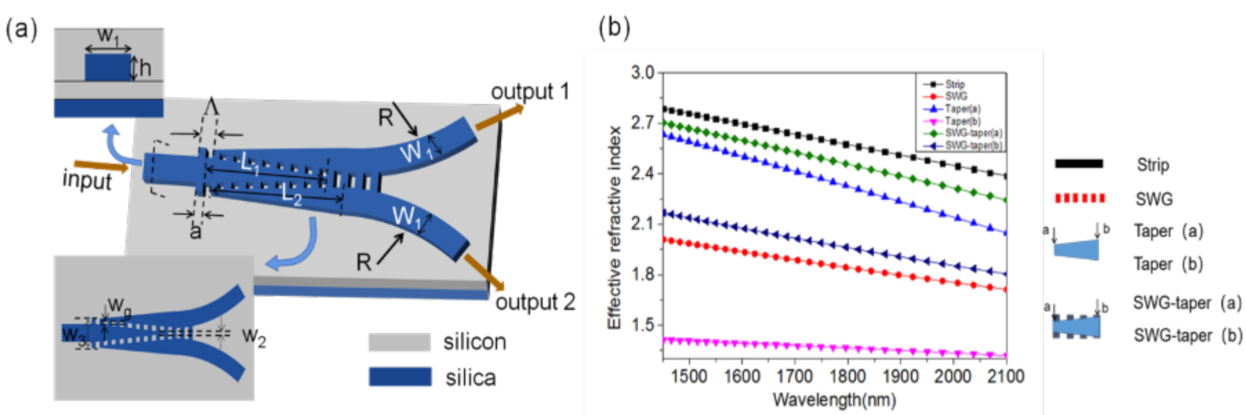

Figure 3.12: (a)Schematic of the proposed silicon-based power splitter, where cross-sectional views of the input waveguide and enlarged views of the SWG-based coupler are also illustrated.(b) Variation of effective refractive index of different structure waveguides with wavelength [11].

110nm, it is compact and easy to produce, and after optimizing the structural parameters, the device shows good simulation results. This power splitter can be a good building block for a large-scale integrated optical switching network with a spectral range of 1.55µm to 2µm, spanning a total bandwidth of over 500nm. Notably, the total length of the device is 3µm, which is much shorter than conventional ultra-broadband power splitters.

This 3dB coupler is built using SWG-assisted tapered waveguides and subwavelength grating on an SOI platform with a 220nm thick silicon layer and 2µm silicon-dioxide buried layer. The three-dimensional (3D) schematic of the proposed ultra-broadband power splitter is shown in the Fig.3.12. The length of the input tapered waveguide is L1, and two inverse-tapered waveguides of the tapered length are L2. The input tapered waveguide and the inverse-tapered waveguides have the same width of the tip as W2. The two inverse-tapered waveguides are connected to two curved waveguides which with a width of W1. The input tapered waveguide, and the front parts of inverse-tapered waveguides are embedded in the SWG grating structure, where the width of the SWG structure is W3, with the same period Λ and duty cycle a/Λ.

Analysis:

- The proposed power splitter operates over an ultra-broadband spectrum, covering the 1.55-µm and 2-µm wavebands. This capability makes it suitable for emerging optical communication windows and addresses the increasing demand for bandwidth.
- The total length of the device is approximately 3 µm, significantly shorter than conventional ultra-broadband power splitters. The compact size benefits integration into high-density photonic integrated circuits (PICs).
- The use of subwavelength gratings (SWGs) and tapered waveguides contributes to the efficient coupling of TE modes. The SWG structure helps adjust the refractive index, enabling smooth mode transfer with low loss.
- The device's performance is sensitive to structural parameters such as the period and duty cycle of the SWG. Achieving optimal values for these parameters requires careful optimization and may be sensitive to fabrication variations.
- The device is specifically designed for TE mode operation. While this is suitable for certain applications, it may limit its versatility in scenarios where both TE and TM modes must be considered.

Design	Exp/ Theory	λ_1-λ_2(nm)	L (µm)	W$_d$ (µm)	Gap (nm)	ER (dB)	IL (dB)	FOM1	FOM (µm)
[7]	Exp	1500-2000	2.125	0.7	130	3.67	0.4	9.19	4.599
[8]	Exp	1860-1970	N/A	N/A	N/A	≥ 15	0.5	30	3.3
[9]	Sim	1500-1570	2	0.18	320	N/A	N/A	N/A	N/A
[11]	Exp	1550-2000	3	0.7	130	-3.97	0.05	-79.4	-35.73

Table 3.3: Performance comparisons of different Y-Coupler designs.

3.5.6 Y-Coupler design parameters:

The table 3.3 summarizes key results from recent research papers on Photonic y-couplers. Several performance parameters and device dimensions are reported that help characterize and benchmark the modulators. The first column indicates if the paper presents experimental or simulated data. The targeted operational wavelength range is listed next, covering infrared telecom bands from 1500 to 2000nm. Compact microring devices a few tens of micrometers in circumference are demonstrated. The microring width of around half a micron supports single fundamental optical mode propagation & enhances intensity modulation efficiency. The nanoscale gaps between microring & waveguides represent precision silicon photonic fabrication at its finest and help yield high-field intensity overlaps. This leads to large extinction ratios (ER)in [8], signifying deep optical modulation depths above 15dB and super low insertion loss below 0.05dB in [11]. Figures of merit combine these modulation metrics to enable comparison. We notice clear performance trade-offs - achieving ultra-low loss and very high ER simultaneously remains challenging. Some parameters are unreported and are indicated as Not Available(N/A) as values are missing and could not be acquired from reference papers.

Paper [8] has the best FOM1(30), but the final FOM is high (4.59µm) in [7] (as per the calculations done).However the value of FOM is small compared to values obtained in other design types.

3.6 Review of Some Emergent Designs of MZI Couplers

3.6.1 Ultra-Broadband Polarisation Beam Splitter Based on Cascaded Mach-Zehnder Interferometers Assisted by Effectively Anisotropic Structures. [12]

Silicon photonics based on silicon-on-insulator (SOI) platforms has the advantages of high index contrast, compact footprint, and compatibility over the complementary metal oxide semiconductor (CMOS). However, the high index contrast results in waveguide birefringence, making the silicon nanophotonic devices polarization-dependent. In order to solve this problem, polarization management is required.One of the most important devices for polarization management is a polarization beam splitter (PBS), which can separate the two orthogonal polarizations.

Zongxing Lin, Kaixuan Chen, Qiangsheng Huang, and Sailing He, the authors of this paper [12], demonstrate and propose an ultra-broadband polarization beam splitter (PBS) consisting of cascaded MZIs on 220 nm thick silicon-on-insulator platform. The point symmetrical configuration of the cascaded MZIs can broaden the working bandwidth for the TM polarization. The SWG structures in DCs act as an effective anisotropic cladding to enhance the separation of the two fundamental polarizations. At the two output ports of the point symmetrical configuration, two filters with two cascaded 180° bends and a Bragg reflection structure have been used to improve the ER further. Calculated results have shown that this proposed PBS has a remarkable performance with ER $\geq$ 20 dB over a record broad bandwidth of 310 nm (IL $\leq$0.5 dB) or 350nm (IL$\leq$1 dB) for both TE and TM polarization inputs.

The device consists of cascaded MZIs and two filters. It is on a 220-nm-thick SOI platform with silicon dioxide upper cladding.When light inputs to port 1, the TE polarization will go through three DCs along its original waveguide and output from port 7 with negligible coupling, while the TM polarization will cause some interference in MZIs and output from port eight finally.The configuration of the cascaded MZIs has point symmetry, which guarantees the broadband output from port 8 for the TM polarization. The bent structure at port seven and the Bragg reflection structure at port eight would filter the remaining TM and TE powers, respectively.

Analysis:

- The proposed polarization beam splitter (PBS) demonstrates an impressive ultra-broadband performance with an extinction ratio (ER) greater than 20 dB over a bandwidth of 310 nm for IL $\leq$ 0.5 dB or 350 nm for IL $\leq$ 1 dB, covering a wide spectral range.

- The proposed photonic device has demonstrated (FOM1= 40 and (FOM)= 16 µm, meeting target performance benchmarks.
- The use of SWG structures allows for effective control over the dispersion relation of the mode in the SWG waveguide, contributing to improved device performance. SWG structures help manage polarization-dependent evanescent wave control.
- The cascaded MZI configuration contributes to broadband operation and efficient polarization splitting. The point symmetrical design aids in achieving broadband output for the transverse magnetic (TM) polarization.
- The transverse electric (TE) polarization is insensitive to variations in waveguide width, while the transverse magnetic (TM) polarization is more sensitive. This sensitivity might pose challenges in fabrication and real-world applications.
- Variations in width between the two arms of the MZI can affect the interference pattern, leading to changes in the performance of the PBS, especially for the TM polarization. This requires careful fabrication control.
- The proposed PBS involves a sophisticated design with multiple components, including SWG structures, MZIs, and filters. Fabrication and integration may be complex, requiring advanced manufacturing techniques.

3.6.2 Sub-wavelength cladding mid-infrared devices [13]

The mid-infrared (MIR) wavelength range waveguides are promising for applications in medicine, biology, communications, defense, and astronomy. Group-IV material platforms are prominent candidates for realizing MIR photonic integrated circuits. For wavelengths longer than 4µm, silicon-on-insulator (SOI) waveguides exhibit high losses due to SiO2 absorption, but removing the SiO2 layer opens up the full transparency range of silicon, up to 8µm.

The researchers Jordi Soler Penades, Milos Nedeljkovic, Ali. Z. Khokhar and Goran Z. Mashanovich, Alejandro Ortega-Monux, Gonzalo Wanguermert-Perez, Robert Halir, and Inigo Molina-Fernandez, Pavel Cheben report an upgrade on their previous work and demonstrate waveguides with propagation losses of 1.2 dB/cm, 90o bends with 0.03 dB/bend loss, compact MMI couplers with imbalances of 0.5 dB, and MZI structures with extinction ratios in excess of 24 dB. Earlier, they demonstrated suspended waveguides with a silicon core and a sub-wavelength grating (SWG) lateral cladding comprising thin silicon strips, which allows access to the buried oxide layer for under-etching with hydrofluoric acid. In this work [13], they show that bends, multimode interference couplers (MMI), and Mach-Zehnder interferometers (MZI) can be successfully implemented on this platform. The width of the silicon support strips is 100nm, and the width of the air gaps is 450nm.

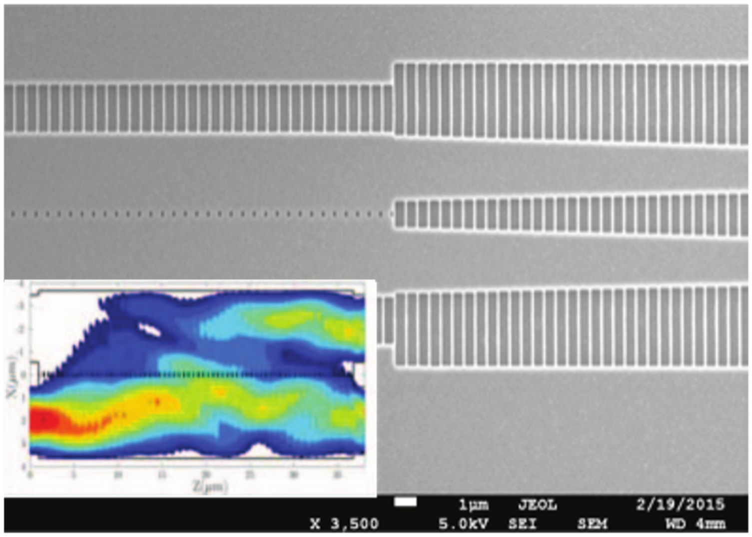

Figure 3.13: SEM image of a shortened MMI with lateral SWG cladding, comprising thin silicon strips [13].

They ensure the sub-wavelength operational regime and allow liquid HF to reach the BOX layer during wet etching. The researchers have widened the waveguide core from 1.1μm to 1.3μm (thus increasing the mode confinement) while reducing the sub-wavelength cladding width from 4μm to 2.5μm so that mechanical robustness is improved, with negligible lateral leakage of the mode. Simulation results at the wavelength $\lambda = 3.8$μm show that the waveguide exhibits negligible lateral leakage losses (< 0.3dB/cm), demonstrating that it is a good alternative to the suspended waveguide. On the other hand, negligible bending losses for curvature radius greater than 15μm are achieved in simulation for both types of waveguides (1.1 μm and 1.3μm core widths). The researchers also designed a conventional 2x2 MMI coupler with lateral SWG cladding. Nominal MMI width and length are 7.1μm and 71.5μm, respectively. The access waveguides were tapered from 1.1μm to 3.1μm at the MMI input/output ports. The sub-wavelength cladding width was reduced to 2μm to improve mechanical stability.

Analysis:

- The introduction of sub-wavelength grating (SWG) holes alongside the waveguide core provides lateral cladding, reducing the effective index and allowing for easy removal of the SiO2 layer.
- Demonstrated devices, such as bends and MMI couplers, exhibit promising characteristics, including low loss, compactness, and high performance.
- While proof-of-concept devices operate at 3.8µm, the design can readily be extended to longer wavelengths, enhancing flexibility for various applications.
- The values of performance metrics are found to be FOM1=18.18, FOM=20.54µm.
- Bending losses for the waveguides are reported as low (0.03dB/90° bend) for tested curvature radii, confirming simulation results.
- The measured imbalance and insertion losses of the Multimode Interference (MMI) devices are within an acceptable range, demonstrating good performance.
- Over-etching during fabrication results in features being slightly smaller than designed, potentially impacting device characteristics.
- Fabricated MMIs are approximately 100nm narrower than designed, potentially affecting their performance compared to simulations.

3.6.3 A Silicon Photonic Ring-Assisted Mach-Zehnder Modulator with Strongly-Coupled Resonators [14]

Mach-Zehnder modulators (MZMs), which are the main component in high-density, high-speed integrated optical transceivers, need to have smaller size and higher energy efficiency to meet the ever-increasing bandwidth demands in data center communications. In this paper [14], Ming Gong, Wuxiucheng Wang, Lejie Lu, and Hui Wu propose a new ring-assisted Mach-Zehnder modulator (RAMZM) based on strongly coupled rings. The new design uses moderately doped PN junction phase shifters to increase the modulation bandwidth.

To achieve 0 to π phase difference between the two arms, an MZM typically requires either high modulation efficiency for its phase shifters or a large RF voltage swing. The MZM phase shifter design has trade-offs between the phase shifter length, optical loss, and RF modulation bandwidth. For PN-junction phase shifters, typically used in high-speed silicon photonic MZMs, the design variables are the cross-section geometries and doping profile. The authors of this paper chose to use Ring-assisted MZMs (RAMZMs) to reduce the phase shifter length and hence the MZM size. It potentially combines the advantages of both MZM and ring modulators, e.g., high extinction ratio (ER), good linearity, and low RF power consumption.

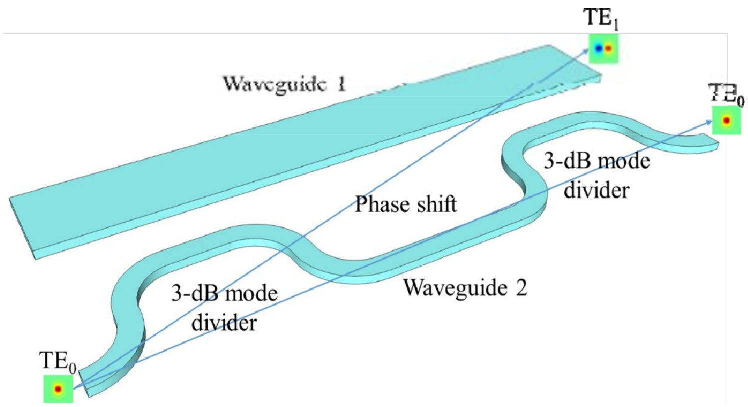

Figure 3.14: Proposed MZI design [14].

Most previous RAMZM designs chose heavily doped PN junctions in the rings to allow low RF voltage swing. In this model of theirs, the researchers decided to reduce the ring-induced insertion loss by designing the rings to be weakly coupled to the waveguides to keep their relatively high Q – this, in turn, results in a long photon lifetime and, hence, a small modulation bandwidth. In this work, the researchers explore new RAMZM designs with strong ring-waveguide coupling and moderately doped PN junctions to achieve a better trade-off between insertion loss and modulation bandwidth.

Analysis:

- Addresses the increasing bandwidth demands in data center communications, emphasizing the importance of smaller size and higher energy efficiency in Mach-Zehnder modulators (MZMs).
- Explores new RAMZM designs with strong ring-waveguide coupling and moderately doped PN junctions to achieve a better trade-off between insertion loss and modulation bandwidth.
- Provides a clear theoretical background on ring resonators and their phase modulation efficiency, emphasizing the trade-off between modulation efficiency and insertion loss.

- The proposed design involves multiple components, including static arm length difference, thermal phase shifters, and optimized PN junction offsets, adding complexity to the system.
- Some limitations in the measurement system are apparent, affecting the eye diagram quality and highlighting challenges in precise characterization.
- Discrepancies between theoretical calculations and experimental results may indicate challenges in achieving precise control over all design parameters.

3.6.4 High-efficiency Silicon Mach-Zehnder Modulator with Vertical PN Junction Based on Fabrication-friendly Strip-loaded Waveguide [15]

In this paper [15], Yuriko Maegami, Guangwei Cong, Morifumi Ohno, Makoto Okano, Kazuto Itoh, Nobuhiko Nishiyama, Shigehisa Arai, and Koji Yamada demonstrate a vertical p-n junction silicon Mach-Zehnder modulator constructed with hydrogenated amorphous silicon strip-loaded waveguides on a flat SOI platform. A 3-mm-long phase shifter shows 0.80- to 1.86-Vcm modulation efficiency, 7.3- to 16.9-dBV loss-efficiency product, 3-dB bandwidth of 17 GHz, and 25-Gb/s operation.

This novel phase shifter structure is designed for silicon optical modulators and is based on hydrogenated amorphous silicon (a-Si:H) strip-loaded waveguides on a silicon-on-insulator (SOI) platform. The SOI layer retains its flatness in the phase shifter, and ions are implanted into it to obtain a uniform doping profile. The optical confinement in the waveguide is provided in the SOI layer by the upper loaded strip, which can be precisely fabricated because there is an etching endpoint layer between the SOI and a-Si:H layer.

This design solves the problem that the rather popular vertical p-n junction structure carries - that of deviation in optical confinement when we try to control precisely the rib height by dry etching with the standard fabrication process. Moreover, obtaining uniform doping carrier profiles is difficult because of the thickness difference between the rib and slab.

The researchers fabricated a strip-loaded waveguide-based optical phase shifter with a vertical p-n junction in this work. The phase shifter can achieve high efficiency with a friendly fabrication process layer. The vertical p-n junction was formed so that low-dose region p+ overlapped low-dose region n+. The p+ and n+ doping levels in the p-n junction were estimated to be about 2 x 1018 cm-3. The high-dose regions for electrical contacts, p++, and n++, were separated by over 1 µm from the waveguide center to avoid carrier absorption loss. After the ion implantation, a 10-nm-thick thermal oxide layer was formed on the flat SOI substrate, which can work as a passivation layer for the electrical structure and an etching endpoint layer in the dry-etching process. Then, an a-Si:H strip-loaded waveguide was constructed by uniformly controlling film thickness through plasma-enhanced chemical vapor deposition (PECVD) and dry etching without any etching of the SOI layer. The a-Si:H strip-line was 800 nm wide and 75 nm thick.

Analysis:

- Introduces a novel phase shifter structure for silicon optical modulators based on hydrogenated amorphous silicon (a-Si:H) strip-loaded waveguides on a silicon-on-insulator (SOI) platform, addressing challenges in conventional designs.
- Proposes a fabrication process that retains the flatness of the SOI layer, and ions are implanted to obtain a uniform doping profile. This process is claimed to be friendly and enables precise fabrication of the strip-loaded waveguide.
- Provides estimates of the propagation loss of the phase shifter and discusses the trade-off relationship between propagation loss and modulation efficiency.
- Claims a low loss-efficiency product, which implies high phase-shifter performance. Compares favorably with loss-efficiency products reported in the literature for similar high-speed silicon modulators.
- Mentions challenges in precisely controlling the rib height in conventional designs due to dry etching, resulting in deviations in optical confinement. Claims that the proposed design solves these issues, but the extent of improvement is not quantified.
- Suggests that the modulation efficiency and speed can be further improved by optimizing the doping profile and decreasing the slight error between the design and fabrication.However, specific details on the error and its implications are not provided.
- While the proposed design is innovative, the complexity of the device structure, involving multiple layers and materials, may pose challenges in large-scale fabrication and integration.

3.6.5 Si-based Mach-Zehnder wavelength/mode multi/demultiplexer for a WDM/MDM transmission system [16]

In this paper [16]of theirs, S. OHTA, T. FUJISAWA, S. MAKINO, T. SAKAMOTO, T. MATSUI, K. TSUJIKAWA, K. NAKAJIMA, AND K. SAITOH report a novel mode MUX based on MZ filter for the combined use of WDM and MDM transmission. Based on a Si-photonics platform, it is a low-loss and low-crosstalk Mach-Zehnder mode/wavelength multi/demultiplexer for WDM/MDM transmission. A newly designed broadband 3-dB mode divider makes composing a broadband MZ "mode" filter possible. The 3-dB mode divider and the MZ mode MUX were fabricated in the CMOS platform. The fabricated device exhibits low-loss and low-crosstalk characteristics in the broad wavelength range and is useful for WDM/MDM transmission.

As the authors mention, there is a limit to the expansion of communication capacity by WDM using a single-mode fiber optical communication system. Therefore, the researchers have experimented with mode division multiplexing (MDM) to attempt further expansion of this communication capacity.In this paper, they propose and experimentally demonstrate a novel MZ mode MUX based on a Si waveguide for WDM/MDM transmission. The transmission spectrum of the proposed MZ "mode" filter is periodic, and at the peak wavelength, the loss and the crosstalk are as small as in a conventional MZ filter.

The proposed MZ mode multi/demultiplexer consists of two 3-dB mode dividers and delay line waveguides. In the mode divider, input TE0 mode from waveguide two is equally divided into TE0 and TE1 mode and TE0 mode has additional phase delay in the delay line. Then, in the second mode divider, two modes are combined and outputted to either port depending on the phase difference. For conventional MZ filters, MMI is often used for a 3-dB divider due to its broadband characteristics.

Analysis:

- The proposed Mach-Zehnder mode multiplexer/demultiplexer (MUX/DMUX) is designed for broadband operation, allowing for the simultaneous use of wavelength division multiplexing (WDM) and mode division multiplexing (MDM) for the expansion of communication capacity.
- The device exhibits low-loss and low-crosstalk characteristics essential for maintaining signal integrity in optical communication systems. This is achieved through a novel 3-dB mode divider and Mach-Zehnder filter.
- The Mach-Zehnder mode MUX can be used for WDM and MDM transmission, providing versatility in designing and implementing communication systems.
- The performance of the fabricated conventional asymmetric directional coupler (ADC) MUX may deviate from theoretical expectations due to fabrication imperfections, leading to increased crosstalk. This indicates a potential challenge in achieving the desired device characteristics during fabrication.

- The conventional ADC MUX shows sensitivity to fabrication imperfections, affecting the crosstalk and overall performance. This sensitivity may limit the robustness of the device in real-world fabrication processes.

3.6.6 MZI design parameters:

Design	Exp/ Theory	λ_1-λ_2(nm)	L (µm)	W$_d$ (µm)	Gap (nm)	ER (dB)	IL (dB)	FOM1	FOM (µm)
[12]	Exp	1350-1750	8	0.55	200	≥ 20	≤ 0.5	40	16
[12]	Exp	1350-1750	N/A	0.6	500	≥ 20	≤ 0.5	40	16
[16]	Exp	1530-1600	27	0.4	250	3.67	0.28	13.10	0.92

Table 3.4: Performance comparisons of different MZI designs.

The table 3.4 summarizes key results from recent research papers on Photonic MZI designs. Several performance parameters and device dimensions are reported that help characterize and benchmark the modulators.The first column indicates if the paper presents experimental or simulated data.The targeted operational wavelength range is listed next, covering infrared telecom bands from 1500 to 2000nm. Compact microring devices a few tens of micrometers in circumference are demonstrated. The microring width of around half a micron supports single fundamental optical mode propagation & enhances intensity modulation efficiency.The nanoscale gaps between microring & waveguides represent precision silicon photonic fabrication at its finest and help yield high-field intensity overlaps. This leads to large extinction ratios (ER)in [12], signifying deep optical modulation depths above 20dB, and super low insertion loss below 0.28dB in [16]. Figures of merit combine these modulation metrics to enable comparison.We notice clear performance trade-offs - achieving ultra-low loss and very high ER simultaneously remains challenging. Some parameters are unreported and are indicated as Not Available(N/A) as values are missing and could not be acquired from reference papers.

Paper [12] has the best FOM1=40, FOM=16µm which makes it clear that this value is far bigger than the other FOM=0.92µm in [16]. (as per the calculations done).

3.7 Review of Some Emergent Designs of MMI Couplers

3.7.1 Subwavelength Grating Waveguide-Based 1310/1550 nm Diplexer [17]

Wavelength Division Multiplexing (WDM) has been a pillar of optical networks for decades. Photonic Integrated Circuits (PICs) can be used to develop diplexers, triplexers, and other components with a significantly smaller footprint. 1310/1550 nm diplexers are essential for developing transceivers that use the O-band and C-band for short-reach interconnections.

The most common platform for passive PICs is SOI for its accessibility and compatibility with CMOS technology. In this paper [17], the researchers Bruno Taglietti and Lawrence R. Chen report an SWG waveguide directional coupler-based 1310/1550 nm diplexer. The fabricated diplexer has an extinction ratio of 23/14 dB at 1310/1550 nm. The total length of the device is 54.4 µm, which is comparable to the length of 55 µm in [18] and much shorter than the device in [50], which is 128.5 µm long. The simulated results showed around 25 dB of ER, while a significant blue shift is seen in the fabricated device. The SWG-based structure allows the researchers to explore a polarization-insensitive version of the diplexer.

This diplexer comprises standard single-mode 500 nm wide solid-core waveguides connected to Vertical Grating Couplers (VGCs) for input and output coupling (optimized for TE mode), two identical SWG waveguides with width wc and length Lc separated by a gap length g, and SWG tapers (with a length Lt = 5 µm to transition between the modes propagating in the solid-core and SWG waveguides). The design aim is to find a coupler length that allows for Lc = nLπ1310 = mLπ1550, where n is an even integer and m is odd.

Integrated WDM multiplexers in silicon-on-insulator (SOI) have been realized using several types of structures, such as directional couplers (DCs), Multimode-Interferometers (MMIs), and Subwavelength Grating (SWG) waveguides. SWG structures provide some advantages, such as the potential for dense integration owing to the ability to make low-loss and low-crosstalk waveguide crossings. Moreover, they allow for the design of polarization-insensitive structures.This paper describes the design, simulation, and characterization of an SWG waveguide DC-based 1310/1550 nm diplexer.

Analysis:

- The diplexer is implemented using Photonic Integrated Circuits (PICs) on a silicon-on-insulator (SOI) platform, resulting in a significantly smaller footprint than traditional components.
- The diplexer is designed for operation at both the O-band and C-band, covering

wavelengths of 1310 nm and 1550 nm. This enables short-reach interconnections with the combined use of these wavelength bands.

- Figure of merit's are obtained as FOM1=41.67, FOM=10.0008µm.
- Subwavelength Grating (SWG) waveguides provide advantages such as low loss, low crosstalk, and the potential for dense integration. Additionally, SWG structures allow for the design of polarization-insensitive components.
- Simulated results show a high Extinction Ratio (ER) of around 25 dB, indicating good performance in separating signals at different wavelengths.
- The fabricated diplexer exhibits a significant blue shift in its response compared to simulation results. This shift is attributed to geometry variations in the SWG structure during fabrication, leading to a potential mismatch between the designed and actual device characteristics.
- The spectral bandwidths of the Vertical Grating Couplers (VGCs) used for input and output coupling are limited. This limitation results in the inability to capture the full spectral response at each port, affecting the accuracy of the measured results.
- The overall fiber-to-fiber loss of 20 dB in the O-band and 15 dB in the C-band is attributed largely to coupling losses of the Vertical Grating Couplers (VGCs). Addressing these losses could improve the overall device performance.

3.7.2 High-Extinction-Ratio and Compact 1310/1550 nm Wavelength Diplexer on SOI Platform Based on an SWG-Structured Two-Mode Interference Coupler [18]

Photonic integrated circuits (PICs) implemented on the silicon-on-insulator (SOI) platform have attracted a lot of attention in recent years because they enable dense integration of photonic devices while remaining compatible with complementary metal-oxide-semiconductor (CMOS) processes. Various silicon-integrated devices have been developed, including 1310/1550 nm wavelength diplexers, which are an essential part of a passive optical network. Different structures have been proposed for this device, mainly including multimode interference (MMI) couplers, directional couplers (DCs), and grating couplers.

The MMI coupler stands out among all the designs mentioned above because of its low insertion loss (IL) and broad bandwidth. Limited by this requirement, a 1310/1550 nm diplexer based on the MMI usually has a large footprint. Efforts have been made to make

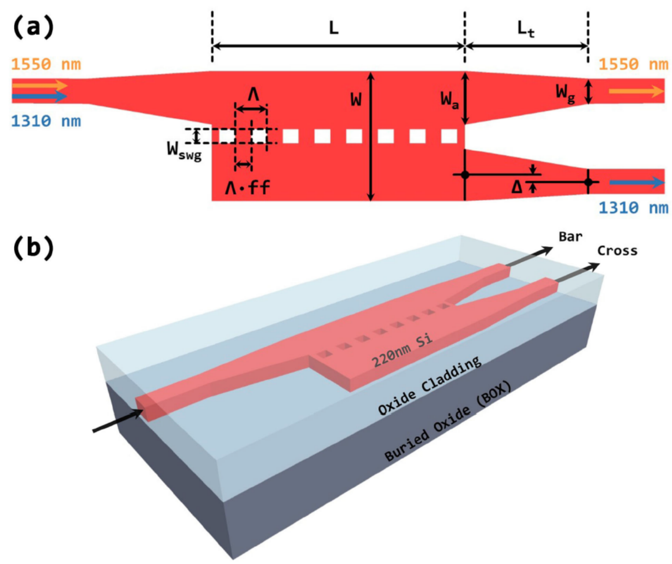

Figure 3.15: (a) 2D and (b) 3D schematics of the proposed device [18].

MMI-based wavelength diplexers more compact, utilizing novel structures such as Bragg gratings, photonic crystals (PCs), and subwavelength gratings (SWGs). Benefiting from advancing fabrication technologies, the SWG has shown its powerful functionality in various silicon photonic devices over the past decade, such as power splitters, microring resonators, polarization beam splitters, and waveguide crossings. Fig 3.15 shows the 2D and 3D view of proposed designs.

Jinsong Zhang, Luhua Xu, Deng Mao, Zhenping Xing, Yannick D'Mello, Maxime Jacques, Yun Wang, Stephane Lessard, and David V. Plant propose a 1310/1550 nm wavelength diplexer [18]on a 220-nm silicon-on-insulator (SOI) platform. The researchers claim this to be the first experimental demonstration of a high-performance compact silicon 1310/1550 nm diplexer based on a TMI coupler. The device is based on a compact two-mode interference (TMI) coupler enabled by a subwavelength grating (SWG) slot. The ideal beat length ratio of 2:1 is achieved with the transverse magnetic (TM) mode by finetuning the SWG slot parameters, resulting in a TMI length of only 37 µm. They reveal that the key to high extinction ratio (ER) is the careful design of the tapers, and the device achieves high ERs of 28.05/42.54 dB at 1310/1550 nm with simulation. Moreover, the design guarantees large calculated 1-dB-insertion loss (IL) bandwidths of 192/123 nm at 1310/1550 nm.

Analysis:

- The proposed diplexer achieves a compact design with a length of only 37 µm, making it relatively smaller than some other reported silicon 1310/1550 nm diplexers.
- The diplexer demonstrates wide bandwidths, with 1-dB-IL bandwidths larger than 120 nm and 15-dB-ER bandwidths larger than 50 nm at both ports.
- The proposed design is experimentally verified, providing practical evidence of its performance.
- The analysis suggests that the proposed structure is insensitive to fluctuations in the SWG fill factor, enhancing the robustness of the device against fabrication variations.
- The experimental results show a shift in the minimum point of the O-band transmission spectrum, deviating from the simulation results. This shift may impact the precise wavelength at which optimal performance is achieved.
- Oscillations are observed in the measured spectra, especially in the O-band. These oscillations may complicate the characterization of specific bandwidth metrics.
- The crosstalk between bar and cross ports, although minimized, is not fully eliminated. The proposed solution involves an offset, and any remaining crosstalk may affect the transmission spectrum.
- The design relies on polarization differences between bands, adding a requirement for polarization control during input coupling, which may increase the complexity of the overall system.

3.7.3 Vertical 2D Grating Coupler for Efficient Multiplexing of Six Modes Between the Few Mode Fiber and SOI Chip [19]

One important trend for advanced optical communication applications is to use a few-mode fiber (FMF) to transmit signals on multiple spatial modes in the same fiber to further increase the net transmission capacity.In the literature, lot of techniques have been developed to achieve this mode division multiplexing (MDM) function, which can be roughly classified as the bulk-optics, fiber-optics, and integrated-optics types. The devices under the category of the integrated-optics type are of particular importance for recent advanced optical communication applications based on silicon photonics chips, which have lot of advantages, including compact size and compatibility with semiconductor IC technologies. In the present work, by using a specially designed 2D grating structure, the authors of this paper show that all the lowest six modes (LP01, LP11a, and LP11b modes for both polarizations) of a few-mode fiber can be multiplexed/demultiplexed from/into silicon photonic waveguides with excellent coupling efficiencies.

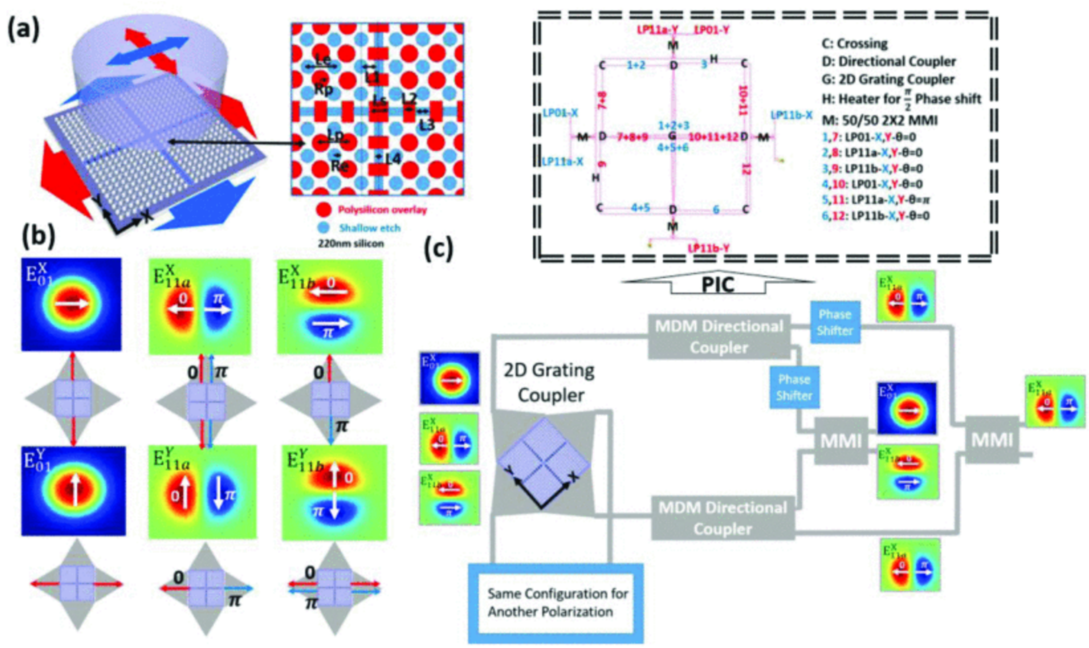

Figure 3.16: Schematic illustration of the 2D grating coupler-based MDM module. (a) Detailed structure of the specially designed 2D grating with crossshaped 1D gratings in the center. (b) The coupling of 3 spatial fibers [19].

Yi-Jang Hsu, Shi-Chieh Hsu, and Yinchieh Lai report a vertical 2D grating coupler [19] that can multiplex/demultiplex three spatial fiber modes in both polarizations between a few-mode fiber and six SOI waveguides with reasonably equalized high efficiencies. The designed MDM 2D grating coupler module capable of separating six modes from the FMF is illustrated in Fig.3.16, which is composed of five parts: the 2D grating coupler (GC), tapered waveguides, waveguide-type MDM directional couplers, phase shifters, and 50/50 MMI couplers. By introducing the cross-line 1D grating structure in the center of the specially designed 2D grating, as illustrated in Fig. 3.16(a), all the modes can be coupled into the opposite two waveguides with equalized intensities. A 2D grating coupler is well known to act as a polarization splitter, which can couple the two input polarizations into the waveguides that are oriented orthogonally to the light polarizations, as shown in Fig.

3.16(a). Fig. 3.16(b) shows how the three spatial fiber modes of the two polarizations are coupled into the four waveguides by the 2D grating. The four waveguides connected by the tapers from the four edges of the 2D gratings are all 2-mode waveguides supporting TE fundamental and first-order modes. In Fig. 3.16(c), the researchers use the x-polarization input case as an example for explanation.

Analysis:

- The proposed device enables MDM by multiplexing/demultiplexing all six modes (LP01, LP11a, and LP11b modes for both polarizations) of a few-mode fiber (FMF). This approach enhances the net transmission capacity in optical communication applications.
- The device falls under the integrated optics category, which is advantageous for advanced optical communication applications using silicon photonics chips. Integrated devices offer a compact size and compatibility with mature semiconductor IC technologies.
- The device takes advantage of the symmetry in coupling the fundamental mode (EX01) and first-order mode (EX11b) to opposite two waveguides. This symmetry aids in separating these modes using a 50/50 MMI coupler for coherent combination with proper active phase bias control.
- The crosstalks to other modes are reported below -17 dB, indicating high isolation between different modes. This low crosstalk is essential for distinguishing between various fiber modes in practical applications.
- The design and simulation results are specific to a wavelength of 1550 nm. While this may be suitable for certain applications, it could limit the device's flexibility in accommodating different wavelengths.
- The device involves a complex structure with multiple components, including the 2D grating coupler, tapered waveguides, MDM directional couplers, phase shifters, and MMI couplers. Fabricating and aligning such complex structures may pose challenges.

3.7.4 Compact silicon-based polarization-independent 1.55/2 μm wavelength diplexer based on a multimode interference coupler with multiple shallow grooves [20]

Faced with the rapid growth of internet traffic demand, which has posed a huge challenge to the current fiber-based communications systems, expanding the telecommunications bands from the traditional near-infrared (NIR) region to the mid-infrared (MIR) region is emerging as an attractive solution. An on-chip wavelength division multiplexing (WDM) application for NIR/MIR wavelengths is essential in future optical telecommunication systems. Wavelength division multiplexing (WDM) technology significantly increases the aggregate bandwidth of an optical transmission system. The WDM scheme uses multiple operating wavelengths as independent channels to carry optical signals.

Yufei Chen, Shengbao Wu, Jiao Zhang, Min Zhu, and Jinbiao Xiao propose a compact silicon-based polarization-independent wavelength diplexer [20] for the NIR/MIR wavelengths of 1.55/2 µm, where multiple rectangular grooves are shallowly etched on the silicon MMI waveguide for introducing the refractive-index perturbations on the MMI waveguide eigenmodes. This refractive-index perturbation scheme provides a simple and scalable method to manipulate the four-beat lengths of the two wavelengths at TE- or Talent Management polarization in a single waveguide via self-imaging effect, leading to a compact footprint. By optimizing the structural parameters, both NIR/MIR wavelength demultiplexing and polarization independence are obtained simultaneously for the first time in the present single device. From the results, the proposed diplexer is only 21.6 µm in length and shows a wide bandwidth of 100/120 nm around the wavelength of 1.55/2 µm for insertion loss (IL) $<$ 1 dB and extinction ratio (ER) $>$ 15 dB. The researchers also realize a compact and polarization-independent wavelength diplexer for 1.31/2 µm by flexibly changing the dimensions, showing the flexibility and extensibility of our refractive-index perturbation scheme.

This diplexer is based on the SOI platform, and the silica (SiO2) is utilized as the upper and bottom cladding material. The device consists of an input waveguide, an MMI section, two output waveguides, and tapered waveguides, which can connect the input/output… In conclusion, utilizing the MMI coupler assisted with SGs, we have proposed a compact and polarization-independent wavelength diplexer for 1.55/2 µm. Owing to the installation of the SGs, the refractive-index perturbations are introduced on the eigenmodes of the MMI waveguide, which can simultaneously manipulate the beat lengths for different operating wavelengths at TE- or TM-polarization by affecting the effective indices of the eigenmodes.

Analysis

- FOM1,FOM calculated for coupling lengths 21.6 µm,18µm are (15,6.75µm), (15,10.35µm) respectively.
- Bandwidth can be extended to 100 nm. Flexibility and extensibility of the proposed design scheme are demonstrated by realizing a compact polarization-independent diplexer for 1.31/2 µm with a total length of 18 µm.
- The proposed diplexers show good performance in terms of insertion loss (IL), reflection

loss (RL), and extinction ratio (ER) for both wavelengths and polarizations. The design methodology involves manipulating beat lengths through shallow grooves, allowing for compact device dimensions. The numerical results are validated using full-vectorial mode solvers and 3D finite-difference time-domain simulations.

- The fabrication tolerance analysis indicates that the proposed diplexers are robust to certain parameter variations, making them promising for practical implementation. The three-step fabrication process on a silicon-on-insulator (SOI) wafer, involving lithography, etching, and cladding deposition, is considered feasible.
- The proposed polarization-independent diplexers for NIR/MIR wavelengths offer a compact and efficient solution for on-chip demultiplexing. The demonstrated flexibility in accommodating different wavelength pairs showcases the potential of the design for diverse applications in optical communication systems.

3.7.5 Polarization Beam Splitter Based on MMI Coupler With SWG Birefringence Engineering on SOI [21]

Polarization beam splitters (PBSs) are essential devices in photonic integrated circuits (PICs) for splitting and combining light with different polarizations. They are widely used in polarization-division multiplexed (PDM) systems to increase the transmission capacity. PBSs have been realized in PICs using directional couplers (DCs), Mach-Zehnder interferometers (MZIs), two-mode interference (TMI) couplers, and multimode interference (MMI) couplers. In this paper, Luhua X, Yun Wang, Amar Kumar, David Patel, Eslam El-Fiky, Zhenping Xing, Rui Li, and David V. Plant demonstrate a novel polarization beam splitter [21] (PBS) based on a subwavelength grating (SWG) multimode interference (MMI) coupler for the silicon-on-insulator platform. The birefringence of the MMI coupler is engineered using SWG, which leads to a compact design footprint with a device length of less than 100 µm.

This PBS has simulated extinction ratios (ERs) better than 20 dB for both polarizations over the wavelength range from 1530 to 1625 nm that covers the entire C- and L-bands. The fabricated device achieves the measured ERs larger than 20 dB at the wavelength of 1550 nm for both polarizations and the insertion losses of 1.9 and 2.5 dB for the transverse electric (TE) and transverse magnetic (TM) polarizations, respectively, at 1550 nm. In addition, the measured ERs are larger than 14.5 dB for the TE polarization and 11.7 dB for the TM polarization over an 84-nm spectral range covering the entire C-band.

Compared to other structures, MMI couplers have the advantage of low loss, ease of fabrication, and relaxed fabrication tolerances. However, they suffer from a large device footprint as the length of the MMI coupler has to be the integer multiples of the beat lengths for both polarizations. In this paper, the authors demonstrate a PBS based on a SWG MMI coupler for the SOI platform. The birefringence of the MMI coupler has been engineered using SWG to achieve a compact device footprint and broadband operation. Their simulations show that the ERs for the TE and TM polarizations at the wavelength of 1550 nm are as high as 35.7 dB and 26.8 dB, respectively, and the ILs are as low as 0.49 dB and 0.28 dB. In addition, the ERs are larger than 20 dB over the entire C and L bands from 1530 nm to 1625 nm.

Analysis:

- The SWG MMI PBS achieves a sub-hundred-micron device length, making it more compact than other MMI-based PBSs.
- The device demonstrates high extinction ratios (ERs) for both transverse electric (TE) and transverse magnetic (TM) polarizations over an 84 nm bandwidth covering the entire C band.
- The insertion losses (ILs) for both TE and TM polarizations are relatively low, especially at the wavelength of 1550 nm.
- The measured performance FOM1- 8, FOM-1.6µm of the fabricated device is not good, mainly due to spectral oscillations for the TM polarization. Improving the fabrication process is necessary to address these challenges.
- The device performance is affected by sidewall roughness and other fabrication imperfections, indicating a sensitivity that could impact consistency in production.

3.7.6 An Ultra-Compact Wavelength Diplexer Engineered by Subwavelength Grating [22]

In this paper [22], Lu Liu, Qingzhong Deng, and Zhiping Zhou report developing an ultra-compact, low loss, and broadband multimode interference (MMI) based diplexer with the assistance of subwavelength grating (SWG). A certain number of SWG pitches are implemented in the middle of the MMI section, which can engineer the effective refractive index for the modes and tune the beat length.With proper tailoring of the grating parameters, the beat lengths of the two wavelengths can be reduced and the device length, which has to match several odd or even times of beat lengths of both wavelengths. As a result, the proposed wavelength diplexer is 43.4 µm in length, which is only 30% of its conventional counterpart. It also displays a wide 1-dB bandwidth of 150 nm around the wavelength of 1310 and 120 nm around the wavelength of 1550 nm. The insertion losses are less than 0.1 dB for the two operating wavelengths, while the extinction ratios are better than 20 dB.

Wavelength demultiplexers play significant roles in optical transmission systems with wavelength division multiplexing (WDM) technology. A variety of SOI diplexer schemes have already been proposed, which (de)multiplex O-band and C-band signals. Diffractive grating couplers couple the two wavelengths in different directions. However, they cannot work for on-chip interconnects but can work for fiber-to-chip optical exchange. Microring resonators filter out different wavelengths on the chip and provide a low insertion loss (IL), but their bandwidth is limited, and extra temperature control is needed. Directional couplers also have the drawback of narrow bandwidth since the phase-matching condition needs to be satisfied. Multimode interference (MMI) based diplexers stand out as the most potential solution, which provides a relatively low IL and a broad bandwidth.

Several groups have reported such wavelength diplexers. Nevertheless, the device length has to match several odd or even times of beat lengths of both wavelengths and usually exceeds 110 µm. But for silicon photonics, compactness, and high integration density are key points. A particle swarm optimization or inverse design algorithm is applied to shrink the length. However, the design procedure is complicated, and the 1 dB bandwidth fails to meet the International Telecommunication Union (ITU) standard.

In this paper, an ultra-compact MMI-based diplexer is proposed, which relies on SWG to manipulate the beat length of both wavelengths and shrinks the device length to only 43.4 µm. Meanwhile, the device performance is good without any deterioration, and the bandwidth is as broad as 150 nm around 1310 nm and 120 nm around 1550 nm, much wider than that of ITU requirements. Its MMI section is as short as 43.4 µm, only 30% of its conventional MMI counterpart. The IL is only 0.09 dB and 0.08 dB for the wavelength of 1310 nm and 1550 nm, respectively, while the ER is better than 20 dB. The bandwidths are as broad as 150 nm and 120 nm for the two output ports, covering the entire O-band and C-band, respectively.The device is mostly sensitive to the fabrication error of the groove, while it is quite robust to the variation of MMI section length.Compact wavelength demultiplexers dealing with more channels can be expected by cascading the proposed diplexer.Furthermore, in principle, the concept of SWG to reduce the device length by tailoring the beat length can be extended to other MMI-based devices.

Analysis:

- The proposed MMI-based diplexer is ultra-compact with a significantly reduced device length (43.4 µm), obtained FOM1-120, FOM-28.8µm, making it suitable for applications with space constraints.

- The diplexer demonstrates a broad bandwidth, covering 150 nm around 1310 nm and

120 nm around 1550 nm, satisfying the ITU standard. This makes it versatile for various wavelength division multiplexing (WDM) applications.

- The diplexer is designed for the silicon-on-insulator (SOI) platform, providing compatibility with complementary metal-oxide-semiconductor (CMOS) technology and enabling integration with other photonic devices.
- The fabrication process involves only one-step lithography and etching, making it relatively straightforward and compatible with standard foundry processes.
- The device performance is most sensitive to variations in groove width (a), and maintaining precise control over this parameter is crucial for optimal performance.
- Although the fabrication process is simple, achieving the required precision for subwavelength grating dimensions may pose challenges.
- The letter provides an overview of the proposed diplexer, but detailed information on the fabrication process, such as the specific lithography and etching techniques used, is not provided.

3.7.7 MMI design parameters:

- The table 3.5 summarizes key results from recent research papers on Photonic MMI designs.Several performance parameters and device dimensions are reported that help characterize and benchmark the modulators.
- The first column indicates if the paper presents experimental or simulated data. The operational wavelength range targeted is listed next, covering infrared telecom bands from 1310nm up to 2000nm.
- Compact microring devices a few tens of micrometers in circumference are demonstrated. The microring width around half a micron supports single fundamental optical mode propagation & enhances intensity modulation efficiency.
- The nanoscale gaps between microring & waveguides represent precision silicon photonic fabrication at its finest and help yield high-field intensity overlaps. This leads to large extinction ratios (ER)in [56], signifying deep optical modulation depths above 50dB, and super low insertion loss below 0.03dB in [54].
- Figures of merit combine these modulation metrics to enable comparison. We notice clear performance trade-offs - achieving ultra-low loss and very high ER simultaneously remains challenging. Some parameters are unreported and are

Design	Exp/ Theory	λ_1-λ_2(nm)	L (µm)	W_d (µm)	Gap (nm)	ER (dB)	IL (dB)	FOM1	FOM (µm)
[17]	Sim	1310-1550	34.4	1	98	25	0.6	41.67	10.0008
[18]	Exp	1310-1550	37	1.2	60	$\geq$28.05	$\leq$ 0.54	51.94	12.46
[50]	Exp	1200-1700	115.5	0.45	N/A	$\geq$20.3	0.34	59.7	29.85
[20]	Sim	1550-2000	21.6	N/A	N/A	$\geq$ 15	$\leq$ 1	15	6.75
[20]	Sim	1310-2000	18	N/A	N/A	$\geq$ 15	$\leq$ 1	15	10.35
[21]	Exp	1425-1625	100	1.5	1000	$\geq$ 20	$\leq$ 2.5	8	1.6
[22]	Sim	1310-1550	43.4	2	60	$\geq$ 10.8	$\leq$ 0.09	120	28.8
[51]	Exp	1310-1550	45	0.5	N/A	N/A	$\leq$ 1.2	N/A	N/A
[52]	Exp	1500-1630	65	0.45	100	24.2	0.20	121	15.73
[53]	Exp	1500-1600	1034	8	N/A	$\leq$ 26.6	N/A	N/A	N/A
[54]	Exp	1500-1600	3.69	2	N/A	4.25	0.03	141.98	14.19
[55]	Exp	1310-1550	41	2.4	N/A	$\geq$ 20	$\leq$ 1	20	4.8
[56]	Sim	1450-1650	30	1	N/A	51.83	0.08	647.87	129.57

Table 3.5: Performance comparison of different MMI designs.

indicated as Not Available(N/A) as values are missing and could not be acquired from reference papers.

- Paper [56] has the best FOM1=647.87, FOM=129.57µm (as per the calculations done). These results stand out significantly, with no other results closely resembling its outcomes.

Chapter 4

Conclusion and Recommendations

4.1 Summary

In this thesis project, the fact that photonic directional couplers are key components in integrated photonic circuits stands reiterated beyond doubt. More than two dozen types of successful experimental implementations of DCs were discussed, highlighting their structure and configurations used to optimize the efficiencies of splitting or combining optical signals with an equal focus on cost of production and compactness. We noted that these advances in the design and structure of PDCs have led to improved performance, increased functionality, and expanded applications in various fields - cutting across optical fiber communication, power switching, and quantum photonics. The analysis and findings presented in this section build upon the targeted device recommendations made in Chapter−3 covering wavelength division multiplexers in Section(3.4.7), Y-branch couplers in (3.5.6), Mach Zehnder interferometers in (3.6.6) and multimode interference (MMI) components in (3.7.7). These recommendations proposed performance benchmarks and optimized design guidelines for each photonic component type.Calculating key figure-of-merit parameters FOM and FOM1, which incorporate optical loss and modulation efficiency metrics, enables comparative evaluation against suggested targets.

4.1.1 Recommendations:

For Multiplexer's The paper [47] has the highest values for FOM1= 625, and [4] FOM=225 µm among recent implementations.
To suggest the best dimensions from the provided table 3.2, we can consider the operating wavelength range, insertion loss, extinction ratio, and both figures of merit FOM1, FOM as desired. It is important to note that the option of selecting dimensions depends on the

specific requirements of your operation. Here are some recommendations:

For Operating Wavelength Range 1300-1600 µm:

$\delta\lambda$=300nm
Width=0.5 µm
Gap=100nm
ER (as large as possible)=25
IL(as low as possible)=0.05
So FOM1=500
FOM=150 µm

For Operating Wavelength Range 1310-1550 µm:

$\delta\lambda$ =240nm
Width=0.5 µm
Gap=100nm
ER (as large as possible) =11
IL(as low as possible)=0.0176
So FOM1=625
FOM=150 µm

For Y-Coupler's The paper [8] demonstrates the highest combined FOM1 of 30, and [7] has the highest FOM of 4.5 µm among recent implementations.
To recommend the best dimensions from the provided tablec3.3, we can consider the desired operating wavelength range, extinction ratio, insertion loss, and figure of merit FOM1, FOM. It's important to note that the choice of dimensions depends on the specific requirements of your application. Here are some recommendations:

For Operating Wavelength Range 1500-2000 µm:

$\delta\lambda$=500nm
Width=0.7 µm
Gap=130nm
ER (as large as possible)=15
IL(as low as possible)=0.05
FOM1=300

FOM=150µm

For MZIs The paper [12] demonstrates the highest combined FOM1 of 40 and FOM of 16 µm among recent implementations.
To recommend the best dimensions from the provided table 3.4, we can consider the desired operating wavelength range, extinction ratio, insertion loss, and figure of merit FOM1, FOM. It's important to note that the choice of dimensions depends on the specific requirements of your application. Here are some recommendations:

For Operating Wavelength Range 1350-1750 µm:

$\delta\lambda$=400nm
Width=0.5 µm
Gap=200nm
ER (as large as possible)=20
IL(as low as possible)=0.05
So FOM1=400
FOM=160 µm

Operating Wavelength Range 1530-1700 µm:

$\delta\lambda$=170nm
Width=0.5um
Gap=200nm
ER (as large as possible)=25
IL(as low as possible)=0.05
FOM1=500
FOM=85 µm

For MMIs The paper [56] demonstrates the highest combined FOM1 of 647.87 and FOM of 129.57 µm among recent implementations.
To recommend the best dimensions from the provided table 3.5, we can consider the desired operating wavelength range, extinction ratio, and insertion loss, and thus calculate the figure of merit FOM1, FOM. It's important to note that the choice of dimensions will be based on the specific requirements of your application. Here are some recommendations:

For Operating Wavelength Range 1310-1550 µm:

$\delta\lambda$=240nm
Width=1 µm
Gap=200nm
ER (as large as possible)=50
IL(as low as possible)=0.08
FOM1=625
FOM=150µm

For Operating Wavelength Range 1550-2000 µm:

$\delta\lambda$=450nm
Width=0.5 µm
Gap=200nm
ER (as large as possible)=15
IL(as low as possible)=0.03
FOM1=500
FOM=225 µm

Other than the recommendations in design parameters, I would like to round up some of the key aspects of PDC design and structure that I explored in this thesis:

Focus on On-Chip Integration:

Almost all the papers and devices discussed in this study had one eye on the "integrability" of directional couplers into on-chip photonic circuits. All devices also aimed at ensuring seamless interfacing with other photonic components on the same chip, making it more accessible for compact and efficient optical devices.

Small is Beautiful: Ultra-Compact Designs:

The researchers discussed in this thesis developed ultra-compact directional couplers with minimal footprints reflecting their stress on compactness as space-constrained photonic devices and applications demand a high degree of miniaturization of components.

Attention on High-Efficiency Coupling:

All designs and structures discussed in this thesis project unequivocally made coupling efficiency enhancement their primary objective; their designs sought to reduce insertion losses to ensure that a minimal amount of optical power is lost when optical signals of light are split or combined. All the devices discussed were improvements in their precursors regarding coupling efficiency.

Contributing to Silicon Photonics:

All devices discussed were noteworthy for their zeal to contribute to the advancement of silicon photonics technology. All devices discussed were solely Silicon directional couplers aiming at improving signal routing and processing efficiencies in silicon photonic devices, enabling on-chip integration of optical and electronic functionalities.

Increased Attention on Polarization Management:

9 papers featured in this thesis project focused on innovating new techniques for improving, managing, and controlling polarization in directional couplers. These devices demonstrated they can handle various polarization states, making them more versatile and robust for applications where polarization control is critical.

Wideband Operational Dynamics:

Almost all PDCs discussed in this dissertation work showed innovations that could make them operable across a broader range of wavelengths to improve efficiencies in optical communication. All the devices featured in this thesis accorded attention to wavelength-division multiplexing (WDM), and they demonstrated they can support simultaneous transmission of multiple optical signals at different wavelengths, increasing data capacity.

Photonics in the Quantum Realm:

The Though none of the papers referenced in this thesis directly addressed quantum photonics applications or use-cases, the featured directional couplers showed innovations in design and structure that have a significant on the devices' capabilities for quantum photonics experiments and applications like quantum key distribution systems, quantum computing, and quantum communication.

Plasmonic and Metamaterial Coupling Strategies:

Three papers I referenced in this thesis discussed innovations in plasmonic and metamaterial-based directional couplers [57] that realized operability at the nanoscale and enabled applications in subwavelength imaging, biosensing, and possibly for unconventional photonic devices (though this aspect was not directly concluded in any of the papers that have featured in this thesis).

Innovations in Fabrication and Manufacturing Techniques:

Three of the papers I discussed in this thesis focused on aspects relating to fabrication ease, costs, and packageability. The PDCs featured here carried design innovations that lend suitability for nanofabrication and 3D printing.
Despite all the time and space constraints, this thesis has sought to discuss advances in the design and structure of photonic directional couplers and how these have expanded their capabilities and applications, making them indispensable components in photonics, optical communication, and quantum technologies.

4.2 Photonics Advancements and Future

The advancements in optical waveguide design have propelled photonics into new realms, facilitating faster data transmission, compact device integration, and diverse applications across telecommunications, healthcare, and environmental sensing.With technology continuously evolving, optical waveguide design is poised to remain a key focus for innovation in the photonics industry. Concurrently, recent strides in optical and photonic directional couplers [58], [59] have expanded their capabilities and applications, fostering innovation across various fields.These advancements [60], coupled with ongoing challenges [61] and developments in waveguide design, underscore the dynamic landscape of photonics research and development.

Photonics Integration and Miniaturization:

One significant trend driving the advancement of directional couplers is the push towards miniaturization and integration. This trend is fueled by the demand for smaller and more compact devices across various industries. Microfabrication techniques, including micro-electro-mechanical systems (MEMS) and semiconductor processes, have played a pivotal role in enabling the development of miniaturized directional couplers [62] that are suitable for integration into complex systems such as integrated circuits (ICs), radio frequency (RF) front-end modules, and photonic integrated circuits.

For instance, advancements in MEMS technology allow for precise fabrication of miniature directional couplers with high precision and repeatability. These miniaturized couplers find applications in portable devices, aerospace systems, and other scenarios where space and weight constraints are critical. Furthermore, semiconductor processes enable the integration of directional couplers into ICs and microelectronic systems seamlessly.

This drive towards miniaturization and integration not only reduces the footprint of directional couplers but also enhances their performance parameters. Through careful design optimization and innovative fabrication techniques, miniaturized directional couplers can maintain or even improve upon characteristics such as coupling coefficient, isolation, and directivity.

The integration of directional couplers into ICs and microelectronic systems enables the development of more compact and efficient electronic devices, including smartphones, Internet of Things (IoT) devices, and wearable technologies. These miniaturized systems benefit from the compact form factor of integrated directional couplers while maintaining the functionality required for various applications.

In essence, the trend towards miniaturization and integration of directional couplers represents a significant advancement in the field, facilitating the development of smaller, lighter, and more efficient electronic and photonic systems across a wide range of applications.

Broadband and Multi-Band Operation:

Traditional directional couplers have historically operated within limited frequency ranges. However, recent advancements in the field are focused on expanding their bandwidth capabilities to meet the growing demands of modern communication systems.One significant development lies in achieving broadband and multi-band operation, allowing directional couplers to effectively operate across a wider frequency spectrum.

Innovative designs and materials play a crucial role in enabling this expansion of bandwidth.For instance, metamaterial-based structures, which exhibit unique electromagnetic properties not found in natural materials, offer novel opportunities for enhancing the performance of directional couplers across broad frequency ranges.By leveraging metamaterials, researchers can engineer directional couplers with tailored electromagnetic responses, thereby extending their operational bandwidths while maintaining high performance metrics such as low insertion loss and high isolation.

Additionally, the integration of reconfigurable circuits within directional couplers presents another avenue for achieving broadband and multi-band operation. Reconfigurable structures allow for dynamic adjustments of the coupler's characteristics, enabling adaptation to varying frequency requirements in real-time. This flexibility is particularly valuable in modern communication systems, such as 5G networks and beyond, where the utilization of diverse frequency bands for different applications necessitates versatile and adaptable components.

The ability of directional couplers to operate across broader frequency spectra is essential for supporting the increasing data rates and diverse communication services demanded by modern wireless networks. By embracing innovative designs and materials, directional couplers can effectively address the challenges posed by the evolving landscape of communication technologies, ensuring compatibility and performance across a wide range of frequency bands. This advancement paves the way for enhanced connectivity, efficiency, and reliability in next-generation communication systems.

High and Low Power Handling:

In applications where power consumption is critical, such as wireless sensor networks and IoT devices, there's a growing emphasis on designing directional couplers with low power consumption. Advancements in circuit design, such as utilizing low-power CMOS processes and optimized architectures, contribute to reducing the energy consumption of directional couplers while ensuring reliable performance.This enables prolonged battery life and enhances the sustainability of energy-constrained systems.

Simultaneously, another significant area of advancement lies in enhancing the power handling capabilities of directional couplers. This is particularly crucial for applications requiring high power levels, such as radar systems, satellite communications, and industrial applications.Advanced materials and innovative design techniques [63] facilitate the improvement of the power handling capacity while maintaining other performance metrics such as insertion loss, coupling coefficient, and isolation.

By concurrently addressing both low-power consumption and high-power handling requirements, directional couplers can effectively meet the diverse needs of various applications, ensuring efficiency, reliability, and sustainability across different operational scenarios.

Low Loss and High Isolation:

Advancements in achieving low loss and high isolation in directional couplers are rapidly progressing, driven by innovations in materials, fabrication techniques, and circuit designs. Researchers are exploring novel materials with low dielectric loss and high conductivity, coupled with advanced fabrication methods such as precision lithography, to minimize signal attenuation and improve isolation. Moreover, metamaterial-based approaches offer promising avenues for tailoring electromagnetic properties to achieve superior performance. Integration with advanced signal processing techniques, including machine learning algorithms, enables dynamic optimization of coupler parameters for consistent performance even in dynamic conditions.Looking ahead, future advancements may involve the exploration of non-reciprocal and quantum-inspired approaches, as well as the integration of intelligent optimization methods, paving the way for directional couplers with unprecedented levels of low loss and high isolation, essential for next-generation communication systems and beyond.

Adaptive and Reconfigurable Functionality:

Adaptive and reconfigurable functionality in photonics involves the ability to dynamically adjust the properties of photonic devices in real-time to adapt to changing operational conditions or application requirements. Recent advances in this field have focused on developing photonic devices with tunable parameters such as refractive index, dispersion, and polarization state, enabling dynamic control of light propagation and manipulation. Future developments in photonics are expected to further enhance adaptive and reconfigurable functionality through the integration of advanced materials, such as phase-change materials and liquid crystals, as well as the incorporation of novel device architectures and control mechanisms. These advancements will enable the creation of dynamic photonic systems capable of self-optimization, adaptive signal processing, and dynamic reconfiguration, with applications ranging from optical communications and sensing to on-chip photonics and quantum photonics [64].

Future and Advancements in Quantum Computing, Sensing and Biophotonics:

In the realm of quantum computing and sensing, specialized directional couplers are poised to play an increasingly pivotal role, showcasing remarkable advancements and promising future developments. These couplers, tailored specifically for quantum applications, exhibit unique properties such as quantum entanglement and coherence preservation. Quantum directional couplers are instrumental in quantum computing and communication networks, enabling the manipulation of quantum states for information processing and secure communication. Looking ahead, advancements in this field will likely involve further refinement of directional coupler designs to enhance their performance and compatibility with quantum systems. Additionally, the integration of directional couplers with biophotonics [65] holds immense potential for applications in biosensing, medical imaging, and diagnostic technologies. By leveraging the unique capabilities of directional couplers, future biophotonics applications may enable non-invasive and highly sensitive detection of biological molecules, facilitating advancements in healthcare and life sciences.

Future Directions:

The future of directional couplers is marked by a convergence of advancements across multiple fronts, driven by innovative materials and interdisciplinary collaborations. Continued exploration of novel materials, such as metamaterials and low-loss dielectrics, coupled with advancements in fabrication techniques, will enable the development of directional couplers with enhanced performance parameters including bandwidth, isolation, and power handling capability.Integration of artificial intelligence (AI) and machine learning (ML) algorithms will revolutionize directional coupler systems, allowing for adaptive and self-optimizing behavior. AI and ML techniques will enable real-time adjustments to optimize performance in dynamic operating conditions, ensuring optimal signal processing efficiency.Furthermore, collaboration across interdisciplinary fields, particularly in quantum-inspired computing and neuromorphic systems, will unlock new capabilities and applications for directional couplers.By leveraging quantum-inspired computing principles and neuromorphic architectures, directional couplers can achieve unprecedented levels of efficiency and functionality, paving the way for innovative solutions in communication, sensing, and computing domains. This multifaceted approach will drive the evolution of directional coupler technology, shaping the future landscape of telecommunications and photonics.

Transformative Impact and Conclusion

As the field of photonics continues to advance, the pivotal role of directional couplers in these developments cannot be overstated. Their ability to manage and control the flow of optical signals lies at the heart of various photonics applications, from quantum technologies to healthcare and beyond.Yet, their significance transcends mere functionality, as the transformative impact of directional couplers extends to shaping the broader landscape of photonics and technology.

The ongoing pursuit of innovation in directional couplers not only enhances communication and electronic systems but also catalyzes groundbreaking progress in fields like quantum computing, biophotonics, and environmental sensing.This transformative potential underscores the critical need for continued interdisciplinary collaborations and research efforts, which serve as the driving force behind pushing the boundaries of directional coupler technology.

In conclusion, the future of directional couplers is marked by a convergence of advancements across multiple fronts, propelled by innovative materials and collaborative endeavors. From miniaturization to broadband operation, from low power consumption to adaptive functionality, directional couplers are poised to undergo continuous evolution, meeting the diverse and evolving needs of modern communication and electronic systems. By embracing these advancements, we pave the way for a new era of highly efficient, versatile, and adaptive directional couplers, heralding unprecedented innovation in the realm of photonics-enabled technologies.

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