Chip-Scale Hollow Photonic Coupler cum Mode Transformer based on 2-D Taper

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This Thesis is Dedicated

to

" the Almighty God"

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Sneha

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Chip-Scale Hollow Photonic Coupler cum Mode Transformer based on 2-D Taper** in the fulfillment of the requirements for the award of the degree of **Master of Science (Research)** and submitted in the **Department of Electrical Engineering, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period from July 2023 to May 2025 under the supervision of Dr. Mukesh Kumar, Professor, Indian Institute of Technology Indore, Indore, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Sneha 23-06-2026

Signature of the Student with Date

(Sneha)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

23/06/2026

Signature of the Supervisor of MS-R Thesis with Date

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Sneha has successfully delivered the MS-Research Oral Examination held on **22/06/2026**.

ABSTRACT

Efficient coupling between conventional optical fibers and deeply subwavelength nanophotonic waveguides remains a major challenge in integrated photonics due to the large mismatch between the micron-scale optical mode of fibers and the nanoscale confined modes of compact waveguides. This thesis presents a Complementary Metal-Oxide-Semiconductor (CMOS)-compatible silicon-based hollow two-dimensional (2-D) taper coupler cum mode transformer for efficient adiabatic conversion of weakly confined photonic modes into strongly confined plasmonic-like modes. The proposed structure employs simultaneous lateral and vertical tapering of a silicon–air hollow geometry, enabling gradual mode compression and enhanced field localization near the silicon–air interface.

The device is numerically analyzed using Ansys Lumerical MODE, Finite-Difference Time-Domain (FDTD), and Eigenmode Expansion (EME) simulations at the telecommunication wavelength of 1550 nm. The optimized plasmonic-like output region consists of a silicon thickness of 150 nm, hollow gap width of 300 nm, and gap thickness of 30 nm. The simulation results demonstrate near-unity normalized coupling efficiency under optimized conditions, with coupling efficiency approaching 0.95–1.0 for suitable gap width, silicon thickness, and taper-length combinations. The coupling efficiency improves with increasing taper length and approaches saturation for longer adiabatic structures, confirming smooth mode evolution, reduced scattering loss, and efficient power transfer from the input photonic mode to the output confined mode. A detailed parametric analysis is carried out to investigate the influence of hollow-core gap width, gap thickness, silicon thickness, taper length, filling material, and operating wavelength on device performance. The effective refractive index varies from approximately 2.5 to below 2.0 along the taper, indicating redistribution of the optical field from the high-index silicon region toward the hollow low-index region. For the output-side gap-thickness analysis, the coupling efficiency increases from nearly 0.45 to close to unity as the gap thickness is optimized, demonstrating improved modal overlap and stronger confinement. The

electric-field enhancement reaches the order of 10^5 for selected silicon thickness and gap-thickness combinations, confirming strong nanoscale field localization and enhanced light–matter interaction. The wavelength-dependent response further shows that the proposed hollow 2-D taper operates effectively near the 1550–1560 nm telecommunication band. Unlike conventional metal-based plasmonic structures, the proposed device achieves plasmonic-like confinement through dielectric mode engineering and high refractive-index contrast, thereby avoiding Ohmic losses associated with metallic interfaces. The proposed hollow 2-D taper coupler therefore provides a compact, CMOS-compatible, and fabrication-feasible platform for fiber-to-chip coupling, nanophotonic sensing, nonlinear optics, and high-density photonic integrated circuits.

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List of Abbreviations

Abbreviation	**Description**
CMOS	Complementary Metal Oxide Semiconductor
EME	Eigenmode Expansion
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
LSP	Localized Surface Plasmon
LSPR	Localized Surface Plason Resonance
MFD	Mode Field Diameter
MODE	Optical Mode Solver
PIC	Photonic Integrated Circuit
PICs	Photonic Integrated Circuits
SOI	Silicon-on-Insulator
SPP	Surface Plasmon Polariton
TE	Transverse Electric
TM	Transverse Magnetic
n_{eff}	Effective Refractive Index
ER	Extinction Ratio
S-Parameter	Scattering Parameter
IC	Integrated Circuit
PIC Platform	Photonic Integrated Circuit Platform
SPPs	Surface Plasmon Polaritons
k-vector	Wave Vector
MZI	Mach–Zehnder Interferometer
TIR	Total Internal Reflection
Q-factor	Quality Factor

Chapter 1

Introduction

1.1 Integrated Photonics

The ever-growing demands for faster data transfer, reduced energy consumption, and increased processing power have highlighted the limitations of traditional semiconductor electronics. Modern applications, particularly data-intensive fields like artificial intelligence and machine learning, require realtime processing of massive datasets, a task that conventional electronics are struggling to keep pace with,

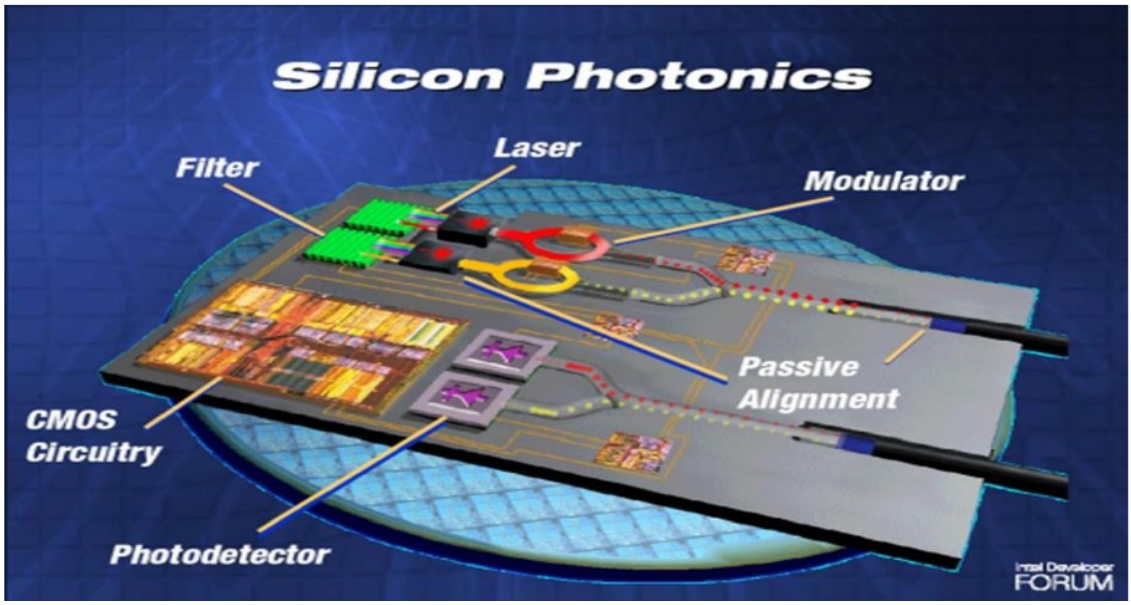


Figure 1.1: Schematic representation of a silicon photonic integrated circuit illustrating the integration of photonic components with CMOS circuitry on a silicon platform. The figure highlights key functional blocks such as optical waveguides, filters, modulators, photodetectors, laser coupling/interface region, and passive alignment structures. These components enable the generation, routing, modulation, filtering, and detection of optical signals on a compact chip-scale platform. The integration of photonic devices with CMOS electronics allows efficient optical signal processing while reducing device size, power consumption, and system complexity.

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Historically shrinking electronic components has led to advancements in speed, power efficiency, affordability, and size reduction. However, this approach is now

approaching its inherent limits. Short-channel effects and fundamental speed and bandwidth constraints are impeding further progress across various scientific and technological disciplines. The expanding gap between processing capabilities and memory bandwidth, as evidenced by the modest 5-10 TDP-FLOP/Byte ratio of current high-performance processors, underscores the critical need for innovative solutions to significantly boost data transfer rates.Electronic interconnects, hindered by latency and losses, pose a substantial obstacle to achieving electronic circuits operating above 10 GHz.

Photonic devices, which utilize light as the information carrier, offer a potential way forward. Nevertheless, the size and complexity of conventional photonic components have, until recently, prevented their seamless integration with. Photonic Integrated Circuits, as illustrated in Figure.1.1, exemplify the successful integration of both passive and active photonic components onto a single substrate. Waveguides, acting as conduits for light,connect these components, enabling the development of compact and robust photonic devices. This integration not only enhances the performance and dependability of photonic functions but also significantly reduces the overall size, weight, and power consumption of these devices[3] electronics on a single chip. The emergence of nanophotonics,a field dedicated to manipulating light beyond its diffraction limit, has revolutionized this landscape. Photonic Integrated Circuits exemplify the successful integration of both passive and active photonic components onto a single substrate. Waveguides, acting as conduits for light, connect these components, enabling the development of compact and robust photonic devices.This integration not only enhances the performance and dependability of photonic functions but also significantly reduces the overall size, weight, and power consumption of these devices.

1.2 Background and Motivation

The relentless advancement of integrated photonics and nanophotonics over the past two decades has been driven by the demand for faster, more compact, and

energy-efficient optical interconnects capable of meeting the growing needs of modern communication, computing, and sensing systems. Optical interconnects are at the heart of these systems, offering unparalleled bandwidth, immunity to electromagnetic interference, and low latency compared to their electronic counterparts. As devices continue to shrink and as photonic integration densities increase, the ability to couple light efficiently between different scales and modalities becomes increasingly critical.

One of the major challenges in realizing high-density photonic circuits lies in bridging the modal gap between standard optical inputs—such as lensed fibers or slab waveguides, which support weakly confined modes with typical mode field diameters of around 10µm—and deeply subwavelength nanophotonic or plasmonic waveguides, which confine light to dimensions as small as 200–300nm or below. The vast difference in mode size and confinement results in a severe mode mismatch, where the overlap between the incident optical mode and the guided mode of the nanoscale waveguide is very small. Consequently, this mismatch leads to large insertion losses, reflection at interfaces, and reduced overall system efficiency. Efficient mode transformation between these vastly different regimes of confinement is, therefore, an essential requirement for practical and scalable nanophotonic devices.

Over the years, several approaches have been developed to tackle this challenge. Grating couplers, for example, diffract incident light into waveguide modes but suffer from limited bandwidth, poor directionality, and high sensitivity to alignment errors. Butt-coupling and end-fire coupling techniques offer direct energy transfer between optical fibers and waveguides but require extremely precise alignment and often suffer from Fresnel reflections and poor confinement control. Inverted tapers have emerged as an attractive alternative, providing a gradual narrowing of the waveguide to improve mode overlap and reduce scattering losses. However, conventional inverted tapers are typically limited to a single axis of tapering (lateral) and do not fully exploit the available degrees of freedom for optimizing mode transformation.

These existing solutions, though promising, still face critical drawbacks, such as abrupt mode transitions, high insertion losses, limited scalability, and fabrication complexities. In the context of plasmonics—where light is coupled into surface

plasmon polaritons (SPPs) confined at the metal–dielectric interface—the challenges are even more pronounced. SPP modes are highly localized, and their coupling with free-space or waveguide modes is inherently inefficient due to their mismatch in wavevector and mode profile. To unlock the full potential of nanophotonics and plasmonics in real-world applications, a more efficient, fabrication-friendly, and compact coupling mechanism is indispensable.

A promising pathway toward addressing these challenges is the concept of adiabatic mode transformation. In this approach, the optical mode evolves gradually along a carefully engineered taper geometry, ensuring that the optical field remains in its fundamental state throughout the transition and avoids exciting higher-order modes or radiative losses. By minimizing abrupt changes in the waveguide dimensions and refractive index profile, adiabatic tapers suppress reflections and scattering while improving mode confinement and energy transfer. Extending this principle further to a dual-axis tapering strategy, where both lateral and vertical dimensions are tapered simultaneously, allows the mode to adapt more effectively to the target nanoscale waveguide while maintaining high coupling efficiency and minimal losses.

In this work, we propose a novel CMOS-compatible, silicon-based hollow 2-D taper coupler cum mode transformer, which leverages the concept of adiabatic dual-axis tapering to overcome the aforementioned limitations. The proposed structure employs a hollow silicon–air configuration, where the optical mode at the wider input end is weakly confined in a silicon layer surrounding an air gap and evolves adiabatically along the taper into a highly confined hybrid plasmonic mode at the narrower output end. The hollow core and dual-axis tapering enable the light to be funneled smoothly from a large mode field diameter to a deeply subwavelength scale while suppressing unwanted higher-order modes, reflections, and scattering losses. This transition results in strong light confinement, enhanced field localization, and efficient energy transfer at the output, where hybrid plasmonic modes dominate.

The choice of a silicon-based design ensures compatibility with established CMOS fabrication processes, facilitating potential large-scale production and integration with existing silicon photonic platforms. Furthermore, the hollow geometry offers

additional degrees of freedom for tuning the optical properties of the taper by modifying the gap dimensions and filling materials, making the device highly versatile for a wide range of applications. The motivation for this work stems from the pressing need to bridge the gap between macro- and nanoscale photonic domains effectively. As optical communication systems push toward higher data rates and integration densities, the ability to couple light efficiently into nanophotonic or plasmonic waveguides becomes a bottleneck. At the same time, applications such as on-chip sensing, quantum information processing, and nonlinear optics require strong light–matter interactions and localized fields, which are enabled by the hybrid plasmonic confinement at the nanoscale. Therefore, a compact, efficient, and scalable coupler that provides high mode purity, strong field enhancement, and fabrication feasibility is of paramount importance.

The proposed hollow 2-D taper addresses these requirements by combining the advantages of adiabatic mode transformation, hybrid plasmonic confinement, and CMOS compatibility in a single, compact structure. By systematically analyzing and optimizing its performance through numerical simulations, this work aims to establish a robust and practical solution for the long-standing problem of efficient light coupling into nanoscale photonic and plasmonic devices.

1.3 Research Objectives

The primary objective of this research is to investigate and address the limitations of existing coupling techniques and to enable efficient light transformation between optical and plasmonic domains, this research focuses on achieving the following objectives.

- To design and optimize a CMOS-compatible, chip-scale hollow 2-D taper coupler incorporating dual-axis tapering (both lateral and vertical) to achieve efficient coupling of light from conventional optical fibers into nanoscale photonic or plasmonic waveguides.

- To demonstrate adiabatic mode transformation, enabling the smooth and gradual evolution of a weakly confined optical mode at the input into a tightly confined hybrid plasmonic mode at the output, while minimizing losses, reflections, and higher-order mode excitation.

- To quantitatively evaluate the performance of the proposed coupler, specifically focusing on key metrics such as mode purity, coupling efficiency, electric field enhancement, and wavelength dependence, through comprehensive numerical simulations.

- To investigate the influence of geometric parameters (e.g., silicon thickness, gap width, taper length) and different filling materials in the hollow core on the overall performance of the coupler, providing insights into its tunability and potential for application-specific optimization.

1.4 Organization of Thesis

This thesis, focused on the development and investigation of a CMOS-compatible hollow 2-D taper coupler cum mode transformer, is structured into distinct chapters as outlined below to ensure a logical flow of concepts, methodology, and results.

Chapter 1: This chapter introduces the motivation, objectives, and structure of this thesis. It begins by highlighting the growing need for efficient, compact, and CMOS-compatible interfaces between conventional optical systems and nanoscale photonic or plasmonic circuits, particularly in the context of integrated optics and on-chip communication technologies. The limitations of existing couplers in terms of mode mismatch, high losses, and poor field confinement are discussed to set the stage for the proposed solution. The chapter clearly states the objectives of the research — to design, simulate, and analyze a hollow 2-D taper coupler cum mode transformer that achieves high mode purity, efficient coupling, and strong field confinement, while remaining fabrication-friendly and compatible with standard CMOS processes. The chapter also outlines the structure of the thesis, providing the reader with a roadmap

of the subsequent chapters, each addressing a specific aspect of the study.

Chapter 2: This chapter focuses on the design principles and theoretical foundation of the hollow 2-D taper coupler. It elaborates on the concept of dual-axis tapering — where both lateral and vertical dimensions of the silicon–air hollow structure are gradually reduced to enable smooth, adiabatic mode evolution from a weakly confined optical mode at the input to a strongly confined hybrid plasmonic mode at the output. The geometric parameters of the device, including the gap width, silicon thickness, taper length, and hollow core configuration, are described in detail, explaining how each influences the mode transformation and coupling performance. The theoretical background on mode confinement, field enhancement, plasmonic effects, and adiabatic transformation is also presented here, laying the foundation for the numerical analyses that follow. This chapter establishes the rationale behind the proposed design and justifies the choices made to meet the stated objectives.

Chapter 3: This chapter presents the core numerical simulations and performance analysis of the proposed coupler. Using tools like Ansys Lumerical FDTD and MODE solvers, the chapter systematically evaluates key performance metrics such as mode purity, coupling efficiency, field enhancement, and wavelength dependence. Detailed results are provided to show how these metrics vary with geometric parameters and material properties, offering insight into the trade-offs involved in optimizing the device. The chapter discusses the evolution of the optical mode along the taper, the field confinement in the hollow core, and the enhancement of light–matter interaction at the output. Figures and plots illustrate how high mode purity and coupling efficiency are achieved at the target wavelength of 1550nm, while also examining how the device performs under variations in gap thickness, silicon thickness, taper length, and refractive index. This chapter demonstrates the robustness and versatility of the proposed coupler in achieving efficient mode transformation.

Chapter 4: The final chapter concludes the thesis by summarizing the key findings and contributions of the research. It emphasizes the effectiveness of the hollow 2-D taper coupler in bridging the modal gap between standard optical fibers and nanoscale photonic or plasmonic waveguides. The chapter underscores the high mode

purity, strong coupling efficiency, significant field enhancement, and compact, CMOS-compatible design achieved through dual-axis tapering and gap engineering. In addition to summarizing the accomplishments, this chapter outlines future research directions, such as experimental fabrication and characterization, material optimization, integration with active devices, and exploration of broadband and application-specific performance. These directions aim to further enhance the practicality and versatility of the device for applications in on-chip communication, sensing, nonlinear optics, and quantum photonics. Furthermore, the chapter discusses possible fabrication challenges, dimensional tolerance issues, and experimental realization strategies for translating the proposed simulation-based design into a practical silicon photonic device.

Chapter 2

Literature Survey

2.1 Introduction

Efficient manipulation, coupling, and transformation of light are fundamental requirements in modern photonic systems, particularly for applications such as optical interconnects, on-chip communication, sensing, and emerging plasmonic devices. Conventional optical coupling techniques, including butt-coupling and grating-based coupling, often suffer from limitations such as high insertion losses, mode mismatch, and limited scalability when interfacing between optical fibers and nanoscale waveguides.Alongwith the rapid advancement of photonic integrated circuits , there is a growing demand for compact, CMOS-compatible, and highly efficient coupling structures. In particular, coupling between dielectric photonic waveguides and plasmonic structures is challenging due to the significant mismatch in mode size and confinement. Photonic modes are typically weakly confined with larger mode areas, whereas plasmonic modes exhibit subwavelength confinement with high field localization. To address these challenges, taper-based mode transformers have emerged as a promising solution. Among them, hollow and hybrid taper structures provide enhanced flexibility in engineering the effective refractive index profile and improving mode overlap. These structures enable gradual mode evolution, reducing scattering losses and improving coupling efficiency. This chapter reviews the existing literature on optical coupling techniques, taper-based mode converters, and photonic–plasmonic integration strategies.

2.2 Coupling and Mode Transformation

Efficient mode transformation is critical for minimizing coupling losses between optical components. Adiabatic tapering is one of the most widely used techniques, where the waveguide geometry is gradually varied to allow smooth transition of optical modes without exciting higher-order modes.

The performance of taper-based couplers depends on several key parameters, including taper length, waveguide dimensions, refractive index contrast, and operating

wavelength. A longer taper generally ensures better adiabaticity but increases device footprint, whereas shorter tapers may introduce radiation losses and mode distortion.

Grating couplers have also been extensively used for coupling light between optical fibers and on-chip waveguides. However, they are inherently wavelength-sensitive and suffer from limited bandwidth and directionality. Edge coupling using inverse tapers provides higher efficiency but requires precise alignment and often lacks compatibility with plasmonic structures.

In recent years, hybrid photonic–plasmonic couplers have gained attention due to their ability to combine low-loss propagation of photonics with strong confinement of plasmonics. These structures typically involve a dielectric waveguide coupled to a metal layer separated by a nanoscale gap, forming a hybrid mode with both dielectric and plasmonic characteristics.

2.3 Review of Taper-Based Photonic and Plasmonic Couplers

J. Van Asch et al.-2024 [12]

This work presents a rigorous and physics-driven methodology for designing adiabatic waveguide couplers in heterogeneous integrated photonic platforms. The proposed approach focuses on achieving highly efficient optical mode conversion between dissimilar waveguide geometries and material systems while minimizing insertion loss, reflection losses, and higher-order mode excitation. The operation of the coupler is governed by the adiabatic evolution principle, where the optical mode gradually transforms along the propagation direction without abrupt perturbation. The adiabatic condition is mathematically expressed as:

$$\left| \frac{\langle \psi_m | \frac{dH}{dz} | \psi_n \rangle}{(\beta_m - \beta_n)^2} \right| \ll 1$$

where β_m and β_n represent the propagation constants of interacting modes, and H denotes the waveguide Hamiltonian. The study employs eigenmode expansion

(EME) analysis and overlap integral calculations to evaluate coupling efficiency and modal evolution throughout the taper region. The overlap efficiency between the interacting optical modes is determined using:

$$\eta = \left| \iint E_1 E_2^* \, dA \right|^2$$

where E_1 and E_2 are the electric field distributions of the input and output modes. Detailed optimization of taper length, refractive index contrast, and waveguide geometry demonstrates broadband coupling performance with strong fabrication tolerance. The work further discusses suppression of non-adiabatic scattering and radiation losses through smooth taper transitions. This research establishes a comprehensive design framework for compact heterogeneous photonic integration, optical interconnect systems, and high-density silicon photonic circuits.

M. Asaduzzaman et al.-2018 [16]

This work proposes a compact silicon grating coupler integrated with a hollow tapered spot-size converter to improve optical coupling efficiency between optical fibers and silicon photonic waveguides. The major challenge addressed in this study is the significant mode mismatch between the large Gaussian optical mode of the fiber and the tightly confined mode of silicon waveguides. To overcome this limitation, the authors introduce a hollow taper geometry that enables gradual mode expansion and adiabatic transformation of the propagating optical field. The coupling efficiency is analyzed through mode overlap calculations expressed as:

$$\eta = \frac{\left| \iint E_f E_w^* \, dA \right|^2}{\left(\iint |E_f|^2 dA \right) \left(\iint |E_w|^2 dA \right)}$$

where E_f and E_w denote the electric field distributions of the fiber and waveguide modes respectively. Finite-Difference Time-Domain (FDTD) simulations are employed to study electromagnetic field propagation and optimize taper dimensions, hollow region geometry, grating period, fill factor, and etching depth. The grating coupler operation satisfies the Bragg phase-matching condition given by:

$$\beta = k_0 n_{eff} = k_0 n_c \sin\theta + \frac{2\pi}{\Lambda}$$

where n_{eff} represents the effective refractive index, n_c is the cladding refractive index, θ is the diffraction angle, and Λ denotes the grating period. The optimized structure demonstrates reduced back reflections, improved bandwidth, enhanced coupling efficiency, and compact device footprint, making it highly suitable for fiber-to-chip optical communication and integrated photonic systems.

D. Chelladurai et al.-2019 [19]

This work demonstrates a low-loss hybrid plasmonic coupler capable of efficiently transferring optical power between dielectric photonic waveguides and plasmonic waveguide structures. The proposed architecture combines the low-loss propagation characteristics of dielectric waveguides with the strong subwavelength confinement capability of plasmonic structures. The coupling mechanism relies on hybrid mode engineering, where dielectric-guided modes interact with surface plasmon polariton modes to achieve efficient energy transfer. The propagation constant of the hybrid mode is expressed as:

$$\beta = k_0 n_{eff}$$

where β denotes the propagation constant and n_{eff} represents the effective refractive index of the propagating hybrid mode. Coupled mode theory is utilized to analyze energy transfer dynamics between interacting modes using:

$$\frac{da_1}{dz} = -j\kappa a_2 e^{j\Delta\beta z}$$

where κ is the coupling coefficient and $\Delta\beta$ denotes the phase mismatch between interacting modes. Detailed electromagnetic simulations are carried out to optimize taper geometry, coupling length, metallic gap size, and field confinement properties. The study demonstrates strong modal overlap, minimized insertion loss, efficient adiabatic mode conversion, and enhanced electromagnetic confinement near the plasmonic interface. The proposed coupler offers significant advantages for compact

plasmonic integration, nanoscale optical routing, and high-density on-chip optical communication systems.

Q. Li and Z. Zhang-2016 [20]

This work investigates bonding and antibonding plasmonic coupling modes in TiO_2-Ag core-shell nanoparticle dimers using electromagnetic hybridization theory and localized surface plasmon resonance analysis. The study demonstrates that when two plasmonic nanoparticles are placed in close proximity, strong near-field electromagnetic interaction leads to splitting of resonance modes analogous to molecular orbital hybridization. The resonance frequency of the localized surface plasmon mode is governed by:

$$\omega_{sp} = \omega_p \left(\frac{1}{1 + \varepsilon_d} \right)^{1/2}$$

where ω_p is the plasma frequency and ε_d denotes the dielectric permittivity of the surrounding medium. The bonding mode exhibits lower resonance energy and stronger electric field localization due to constructive coupling, whereas the antibonding mode results from destructive interaction between adjacent plasmonic oscillations. The localized field enhancement is quantified through:

$$|E|^2/|E_0|^2$$

where E_0 represents the incident electric field amplitude. The work further investigates the effects of interparticle separation, shell thickness, dielectric environment, and nanoparticle geometry on resonance wavelength shifting and field enhancement characteristics. The proposed plasmonic dimer structure demonstrates strong nanoscale electromagnetic confinement suitable for biosensing, nanoantenna design, surface-enhanced Raman spectroscopy, and subwavelength photonic device engineering.

Y. Sui et al.-2022 [21]

This work explores long-range plasmonic interference and localized electromag-

netic field enhancement within periodic nanofinger lattice structures. The proposed metallic nanofinger arrays support localized surface plasmon resonances and collective electromagnetic interactions between neighboring nanostructures, leading to significant enhancement of near-field intensity distributions. The localized electric field enhancement is quantified using:

$$G = \frac{|E_{loc}|^2}{|E_0|^2}$$

where E_{loc} denotes the localized electric field intensity and E_0 represents the incident field intensity. Numerical simulations and experimental investigations demonstrate that constructive interference between adjacent nanofingers produces strong electromagnetic confinement and extended plasmonic coupling over larger spatial regions. The study examines the influence of nanofinger geometry, lattice periodicity, polarization conditions, and excitation wavelength on resonance characteristics and field localization efficiency. The enhanced plasmonic behavior achieved in the proposed structure offers significant potential for ultrasensitive refractive index sensing, nonlinear optical interactions, optical trapping, and surface-enhanced spectroscopic applications.

G. Singh et al.-2017 [32]

This work demonstrates the generation of highly localized plasmonic electromagnetic fields on an integrated photonic platform using tapered plasmonic couplers for biosensing applications. The proposed structure enables efficient mode transformation between dielectric photonic modes and surface plasmon polariton (SPP) modes through a gradually tapered coupling geometry. The propagation constant of the plasmonic mode is governed by:

$$\beta_{SPP} = k_0\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$

where ε_m and ε_d denote the dielectric constants of the metallic and dielectric media respectively. The taper structure enables adiabatic compression of optical energy into nanoscale regions while minimizing scattering and radiation losses. Finite

Element Method (FEM) simulations reveal strong electromagnetic field enhancement near the taper tip along with improved refractive index sensitivity. The study further investigates mode evolution, field confinement characteristics, coupling efficiency, and propagation dynamics as functions of taper geometry and waveguide dimensions. The demonstrated integrated photonic-plasmonic platform provides compact device footprint, enhanced optical sensitivity, and efficient nanoscale light confinement for advanced biosensing and lab-on-chip photonic applications.

2.4 Challenges in Existing Coupling Techniques

Despite significant progress, several challenges remain in designing efficient photonic–plasmonic couplers:

- **Mode mismatch:** Large disparity between optical and plasmonic mode profiles leads to coupling inefficiencies.
- **High insertion loss:** Abrupt transitions and non-adiabatic designs result in scattering and radiation losses.
- **Fabrication constraints:** Nanoscale gaps and complex geometries pose challenges for CMOS-compatible fabrication.
- **Trade-off between footprint and performance:** Longer tapers improve efficiency but increase device size.
- **Limited tunability:** Many designs lack flexibility for optimization across different wavelengths and applications.

These limitations highlight the need for improved designs that can achieve efficient mode transformation while maintaining compactness and fabrication feasibility.

2.5 Research Objectives

The primary objective of this research is to design and analyze a CMOS-compatible chip-scale hollow 2-D photonic taper coupler capable of efficiently transforming and coupling optical modes from conventional photonic waveguides into deeply confined plasmonic-like subwavelength modes. The work aims to overcome the fundamental mode mismatch problem between standard optical fibers and nanoscale photonic/plasmonic integrated circuits while maintaining compact device dimensions, low propagation loss, and high field confinement.

The specific objectives of this work are as follows:

1. To design and optimize a silicon-based hollow 2-D taper coupler structure capable of achieving smooth adiabatic mode evolution from weakly confined photonic modes at the input end to highly confined plasmonic-like modes at the output end through simultaneous lateral and vertical tapering. The objective also includes establishing geometrical conditions necessary for stable mode propagation, efficient field squeezing, and enhanced confinement within subwavelength hollow regions.

2. To numerically investigate the propagation dynamics, modal evolution, and electromagnetic field distribution inside the proposed taper structure using Eigenmode Expansion and Finite Difference Time Domain simulation techniques at the telecommunication wavelength of 1550 nm. This includes studying the influence of high refractive index contrast, dielectric mode compression, and field redistribution at the silicon-air interface responsible for plasmonic-like confinement behavior.

3. To evaluate the optical performance of the proposed hollow taper coupler by analyzing important device parameters such as coupling efficiency, mode conversion efficiency, transmission characteristics, mode purity, and suppression of higher-order modes using scattering parameter (S-parameter) analysis and modal decomposition techniques. The objective further includes quantifying

the effectiveness of optical power transfer from the photonic input region to the nanoscale plasmonic-like output region while minimizing radiation loss, reflection, and modal mismatch.

4. To investigate electric-field enhancement ($|E|^2$ enhancement), subwavelength optical confinement, and localized electromagnetic field concentration at the taper output region. This objective focuses on understanding the relationship between taper geometry, hollow-core dimensions, silicon thickness, and nanoscale mode compression in achieving strong light confinement suitable for enhanced light-matter interaction, biosensing, nonlinear optics, optical trapping, and nanoscale photonic applications.

5. To perform a comprehensive parametric analysis of the proposed device by studying the effect of taper length, air-gap width, silicon thickness, refractive index contrast, and wavelength variation on coupling efficiency, field enhancement, adiabatic mode evolution, and plasmonic-like behavior. The objective also includes investigating wavelength-dependent characteristics and identifying optimized structural parameters for broadband and telecommunication-band operation.

6. To develop a compact, low-loss, highly integrated, and fabrication-compatible nanophotonic coupling platform suitable for future silicon photonic and plasmonic integrated circuits. The objective further aims to establish the proposed hollow 2-D taper coupler as a versatile interface for efficient fiber-to-chip integration, nanoscale optical interconnects, hybrid photonic-plasmonic systems, and next-generation high-density on-chip optical communication and sensing applications.

Chapter 3

Chip-Scale Hollow Photonic Coupler cum Mode Transformer based on 2-D Taper

3.1 Introduction

Efficient light coupling and mode transformation are fundamental requirements in modern nanophotonic and plasmonic integrated circuits. Conventional optical fibers and dielectric waveguides support comparatively large optical modes, whereas nanoscale photonic and plasmonic devices require deeply confined subwavelength modes, leading to significant mode mismatch and coupling losses. The proposed silicon-based hollow 2-D taper structure enables efficient transformation of photonic modes into strongly confined plasmonic-like modes through dielectric mode compression and enhanced electromagnetic field localization at the silicon-air interface.

3.2 Proposed Device Design

The proposed structure is a novel chip-scale two-dimensional (2-D) hollow taper coupler cum mode transformer, which is carefully engineered to achieve efficient light coupling and mode transformation at the nanoscale. The structure exhibits a tapering profile along two directions — the lateral width and the vertical thickness of the coupler — enabling a controlled and gradual transformation of optical modes. This unique tapering in both dimensions ensures enhanced optical confinement, efficient light propagation, and smooth transition from photonic to plasmonic regimes, making it highly suitable for integrated photonic circuits and nano-photonic devices.

Figure 3.1 illustrates the three-dimensional schematic of the proposed device. The device is designed using a two-dimensional CMOS-compatible hollow tapered structure, fabricated entirely from silicon, ensuring compatibility with standard CMOS fabrication processes. The hollow core configuration, where air is enclosed within the silicon walls, provides a distinct advantage by enhancing light confinement in the desired modes while simultaneously reducing propagation losses compared to traditional solid waveguides. The silicon–air–silicon arrangement also contributes to superior modal control, enabling efficient optical signal transmission even at deeply sub-wavelength dimensions. At the input end, where the waveguide is wider

and thicker, the optical modes are weakly confined within the silicon, resembling conventional photonic modes. As the light travels along the taper, the silicon walls gradually narrow in both thickness and width, forcing the mode to shrink and confine more tightly toward the hollow core. At the narrower end of the taper, the mode evolves into a strongly confined hybrid plasmonic mode, exhibiting properties of both photonic and plasmonic fields. A key design aspect of the proposed coupler

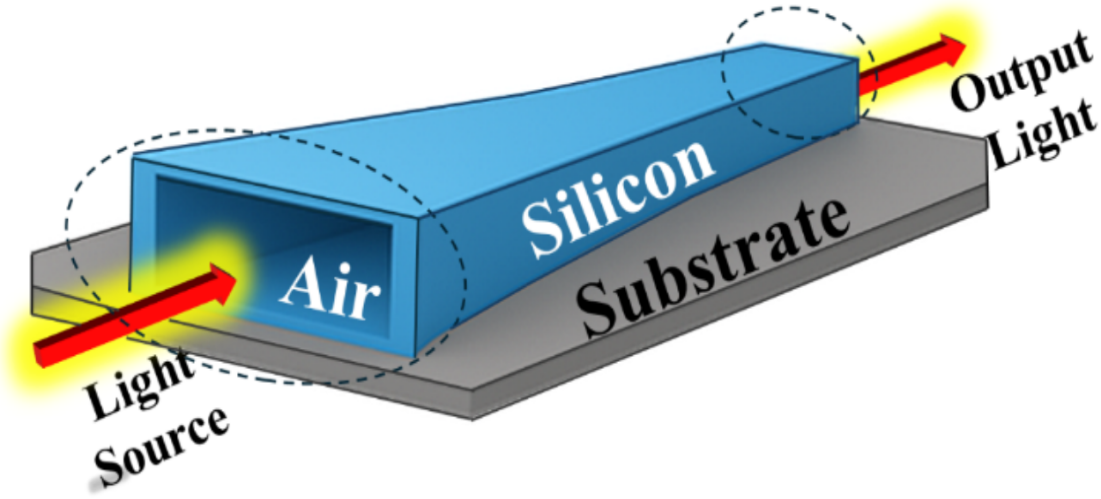


Figure 3.1: Three-dimensional schematic of the proposed compact hollow silicon-based chip-scale photonic coupler cum mode transformer. The structure consists of a dual-axis hollow taper in which both the lateral width and vertical thickness are gradually reduced along the propagation direction. This geometry enables smooth adiabatic transformation of a weakly confined photonic input mode into a strongly confined plasmonic-like mode at the nanoscale output region.

is its CMOS compatibility, which allows it to be fabricated alongside other silicon photonic components using established semiconductor manufacturing techniques.The overall geometry of the proposed hollow 2-D taper coupler is shown in Fig. 3.1. The structure is designed to achieve gradual mode compression by simultaneously tapering the silicon width and thickness along the direction of propagation. “‘ The device employs a dual-axis tapering scheme, where the silicon hollow core is symmet-

rically surrounded by silicon walls in both the horizontal and vertical directions. This symmetrical tapering ensures uniform mode confinement and minimizes scattering losses during the mode evolution process.

As depicted in Figure 3.1, the light is initially coupled into a rectangular silicon input waveguide, with dimensions suitable for interfacing with standard fiber optics. Once inside the device, the light gradually propagates through the 2-D taper, where the hollow core and narrowing silicon walls compress and guide the mode toward the output.

The output end of the taper supports hybrid plasmonic modes with much stronger confinement, enabling interaction with nanoscale devices or plasmonic components that require high field intensities. Importantly, the device is optimized to operate at a wavelength of 1550 nm, lying within the standard telecommunications band.

In summary, the proposed chip-scale 2-D hollow taper coupler cum mode transformer provides a compact, efficient, and CMOS-compatible solution for coupling light from micron-scale fibers into deeply confined hybrid modes in nanoscale devices.

3.3 Analysis of Nanophotonic Confinement

Nanophotonic confinement plays a critical role in achieving efficient light manipulation and mode transformation in deeply subwavelength optical structures. In the proposed hollow 2-D taper coupler, strong electromagnetic confinement is achieved through simultaneous lateral and vertical tapering of the silicon structure. As the optical mode propagates along the taper, the gradual reduction in silicon dimensions compresses the optical field toward the nanoscale hollow air region, resulting in enhanced field localization and plasmonic-like confinement behavior. The dual-axis tapering mechanism enables smooth adiabatic mode evolution while minimizing reflection, scattering losses, and higher-order mode excitation.

Figure 3.3.4 illustrates the optical mode evolution and propagation characteristics within the proposed hollow 2-D taper structure. The figure demonstrates the gradual transformation of the optical field from a weakly confined photonic mode

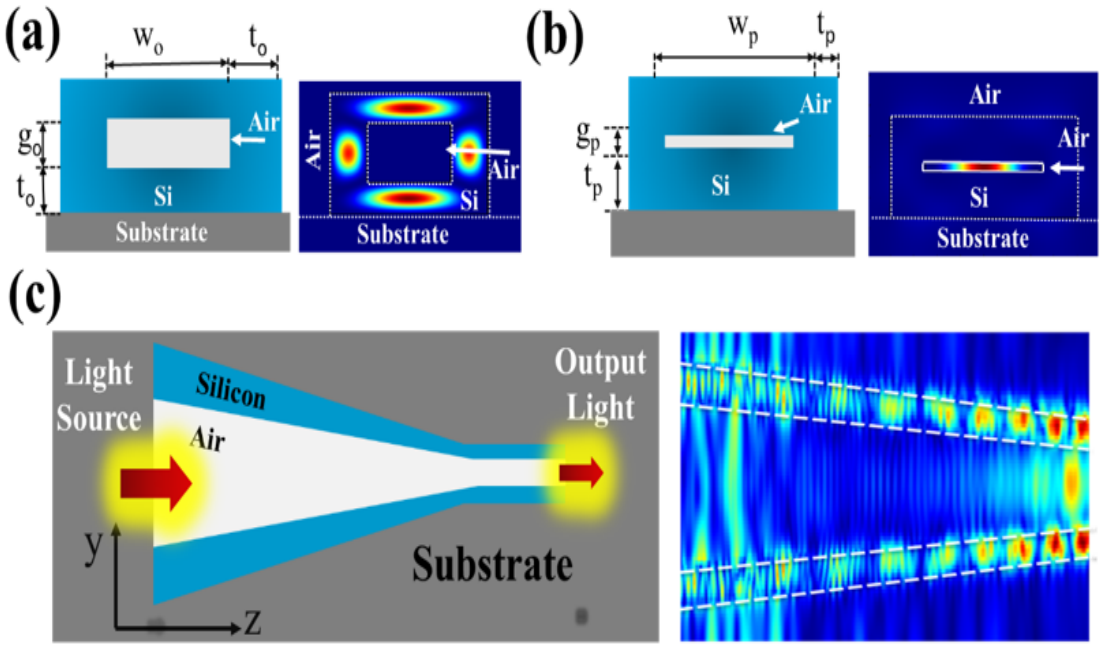


Figure 3.2: Three-dimensional schematic and optical mode evolution of the proposed hollow 2-D taper coupler. (a) Cross-sectional view of the wider input region, where the optical field is weakly confined and resembles a conventional photonic mode. (b) Narrow output section of the taper, showing strong localization of the optical field near the silicon–air interface and formation of a plasmonic-like confined mode. (c) Propagation of the optical field through the hollow taper, demonstrating gradual adiabatic mode compression, reduction in modal area, and enhanced nanophotonic confinement along the taper length.

at the wider input section to a strongly confined plasmonic-like mode at the taper output region. The corresponding field distributions and propagation profiles confirm efficient dielectric mode compression, smooth adiabatic mode evolution, and enhanced electromagnetic field localization near the silicon–air interface.

Furthermore, the gradual reduction in modal dimensions results in a decrease in the effective modal area, thereby increasing the optical energy density inside the hollow region. The enhanced confinement behavior facilitates stronger interaction between the electromagnetic field and the surrounding medium, leading to improved light localization characteristics. Such efficient nanophotonic confinement enables

effective manipulation of optical energy at dimensions below the diffraction limit. These characteristics make the proposed hollow taper structure highly suitable for applications involving integrated nanophotonic devices, optical sensing, nonlinear optical systems, and compact photonic circuits.

3.3.1 Mode Evolution in the Hollow 2-D Taper

The gradual evolution of the optical mode inside the proposed hollow 2-D taper structure is illustrated in Fig 3.2 (a) and Fig. 3.2 (b). The propagation characteristics reveal the transition of the optical field from a weakly confined dielectric mode at the wider input region to a highly localized and strongly confined mode at the nanoscale output region. This gradual transformation plays a critical role in achieving efficient optical coupling and enhanced electromagnetic confinement.

At the wider input region shown in Fig 3.2 (a), the silicon dimensions are comparatively larger, resulting in a relatively lower refractive-index contrast between the guiding region and the surrounding medium. Consequently, the propagating optical mode spreads over a larger effective modal area and exhibits characteristics similar to a conventional dielectric photonic mode.

As the optical wave propagates along the taper structure, both the width and thickness of the silicon layers decrease gradually along the propagation direction. The continuous reduction in geometrical dimensions modifies the effective refractive index of the guided mode and progressively alters the field distribution.

The narrowing of the taper dimensions reduces the effective modal volume and forces stronger localization of the optical field near the silicon–air interfaces. Consequently, electromagnetic energy becomes concentrated within a smaller spatial region, leading to enhanced local field intensity and improved optical confinement.

Figure 3.2 (b) illustrates the field distribution at the narrower output region of the taper structure. At this stage, the electromagnetic field becomes strongly localized near the silicon–air interface and occupies a significantly smaller modal area compared to the input region.

The dual-axis tapering mechanism ensures smooth adiabatic mode evolution

throughout the propagation process. Since the geometrical transition occurs gradually in both lateral and vertical directions, abrupt discontinuities are avoided. This suppresses higher-order mode excitation, minimizes scattering losses, and reduces unwanted reflections.

The observed mode evolution demonstrates the effectiveness of the proposed hollow taper design in achieving strong optical confinement and efficient field localization.

3.3.2 Electric-Field Confinement and Plasmonic-Like Behavior

The confinement behavior observed in the proposed hollow 2-D taper structure resembles hybrid plasmonic confinement because the optical energy becomes strongly localized within a deeply subwavelength region near the silicon–air interface. In conventional plasmonic waveguides, strong optical confinement is usually achieved at a metal–dielectric interface through the excitation of surface plasmon polaritons (SPPs). Such modes arise due to the collective oscillation of free electrons in the metal and can confine light far below the diffraction limit. However, this strong confinement is generally accompanied by significant Ohmic loss because a considerable portion of the electromagnetic energy penetrates into the metallic region. As a result, conventional plasmonic devices often suffer from high propagation loss, heating, and limited transmission length. In contrast, the proposed hollow taper does not employ any metallic layer for field confinement. The plasmonic-like behavior in this structure is achieved entirely through dielectric mode engineering, high refractive-index contrast, and gradual geometrical compression of the optical mode. As the optical field propagates from the wider input region toward the narrower output region, the simultaneous reduction in lateral width and vertical thickness modifies the effective refractive index distribution along the taper. This gradual variation forces the optical mode to shrink progressively and become concentrated near the silicon–air interface and inside the hollow nanoscale

region. Therefore, the output mode exhibits plasmonic-like characteristics such as strong field localization, reduced modal area, and enhanced optical energy density, although it is not a true metal-supported plasmonic mode. The term "plasmonic-like mode" is therefore used in this thesis to indicate that the confined mode shows field localization behavior similar to plasmonic modes, but its physical origin is different from conventional surface plasmon polariton propagation. Instead of relying on free-electron oscillations in metals, the proposed structure obtains strong confinement through the dielectric contrast between silicon and air and through the adiabatic compression provided by the hollow 2-D taper geometry. This distinction is important because it allows the structure to retain the advantages of plasmonic confinement while avoiding the major limitation of metal-induced absorption loss. Consequently, the proposed design provides a low-loss and CMOS-compatible route for achieving nanoscale optical confinement. The gradual redistribution of the electromagnetic field toward the hollow core also enhances the interaction between light and the surrounding medium. Since the optical field is compressed into a smaller effective modal volume, the local electric-field intensity increases significantly near the taper output. This enhanced field localization is beneficial for applications where strong light–matter interaction is required, such as nanoscale optical sensing, nonlinear optics, optical trapping, and compact photonic integrated circuits. Thus, the proposed hollow taper structure acts as a bridge between conventional dielectric photonic waveguides and deeply confined plasmonic-like nanophotonic modes, enabling efficient mode transformation without introducing metallic propagation losses. "‘

3.3.3 Mode Compression and Field Enhancement

Figure 3.2 (c) illustrates the propagation behavior of the optical field along the hollow taper structure. The optical mode launched at the wider input region gradually undergoes adiabatic compression along the propagation direction (z-direction).

The electric-field enhancement inside the hollow taper structure can be expressed as:

$$|E|^2_{\text{enhancement}} = \frac{|E_{\text{localized}}|^2}{|E_{\text{input}}|^2} \tag{3.1}$$

where $E_{\text{localized}}$ represents the localized electric-field intensity near the taper output and E_{input} denotes the electric-field intensity at the input region.

The field propagation profile shown in Fig. 3.3(C) confirms smooth adiabatic evolution of the optical mode with minimal radiation loss and scattering. Near the taper output, strong electric-field enhancement is observed due to subwavelength confinement.

The enhanced field intensity and reduced modal area achieved in the proposed structure are highly advantageous for high-density nanophotonic integration and applications requiring strong light localization. The compact footprint and efficient confinement behavior of the proposed hollow taper coupler make it a promising candidate for next-generation photonic and plasmonic integrated devices.

3.3.4 Nanoconfinement of Light in CFET-like Structure

The motivation for including the CFET-like structure in this work is to examine whether the nanophotonic confinement mechanism observed in the proposed hollow 2-D taper can be extended toward future transistor-inspired three-dimensional architectures. Complementary Field-Effect Transistors (CFETs) are considered promising candidates for next-generation high-density electronic integration because they employ vertically stacked N-type and P-type device regions within a compact footprint. Such vertical stacking naturally introduces multiple silicon–dielectric interfaces, which can strongly interact with confined optical fields. Therefore, the CFET-like structure is investigated in this thesis to explore the possibility of localizing optical energy within vertically stacked nanoscale regions and to establish a connection between advanced CMOS-compatible transistor architectures and nanophotonic confinement. The relevance of this study lies in the growing need for heterogeneous integration of electronic and photonic functionalities on the same chip. Future integrated systems may require optical interconnects, sensors,

modulators, and transistor-level electronic devices to coexist within a compact platform. In this context, a CFET-like geometry provides an interesting structure for analyzing how light can be confined and redistributed in multiple vertically stacked active regions. If optical energy can be localized efficiently near both the upper and lower silicon–dielectric interfaces, such architectures may support enhanced light–matter interaction, compact optoelectronic coupling, and nanoscale sensing within CMOS-compatible device platforms. In the present analysis, the CFET-like structure is not proposed as a complete electronic transistor device but is used as a representative stacked nanoscale geometry to study optical confinement behavior. The normalized electric-field distribution is used to examine whether the optical field remains confined within the stacked regions and whether strong field localization can be achieved near the silicon–dielectric interfaces. This study therefore strengthens the broader objective of the thesis by showing that the proposed confinement concept is not limited only to the hollow taper coupler, but may also be extended toward future vertically integrated photonic–electronic structures.

Figure 3.3.4 illustrates the proposed CFET-like optoelectronic structure and its corresponding optical confinement characteristics. Figure 3.3.4(A) presents the schematic representation of the vertically stacked CFET architecture consisting of P-type and N-type silicon regions surrounded by dielectric layers, while Fig. 3.3.4(B) shows the normalized electric-field distribution inside the structure. The figure demonstrates efficient localization and redistribution of optical energy inside the stacked nanoscale device geometry. Initially, optical confinement behavior was investigated in a FinFET-based structure where light was observed to be confined within the SiO_2 region due to the refractive-index contrast between silicon and the surrounding dielectric medium. The obtained field distribution demonstrated successful localization of optical energy near dielectric interfaces and confirmed the possibility of realizing optoelectronic confinement behavior in transistor-like structures.

Motivated by the confinement characteristics observed in FinFET structures, the study was further extended toward a CFET-like architecture to investigate

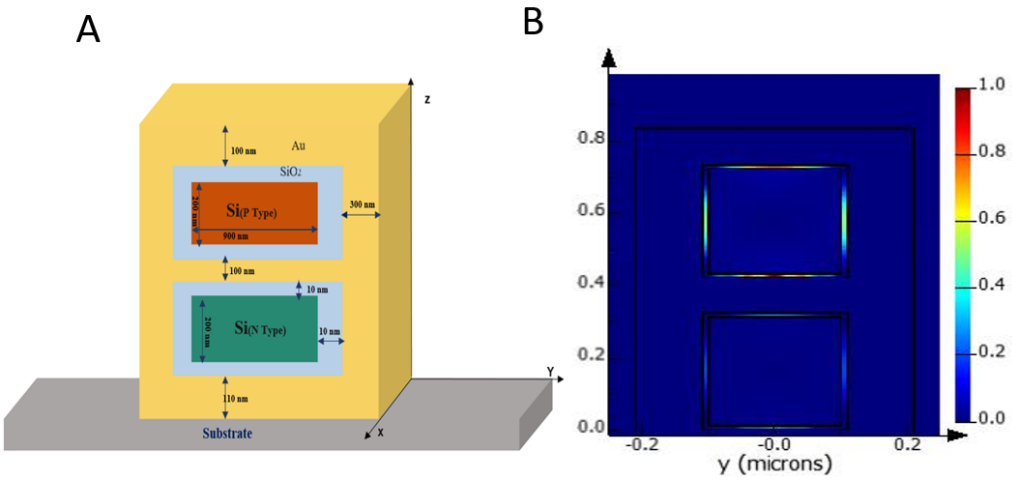


Figure 3.3: Schematic representation and optical confinement behavior of the proposed CFET-like nanophotonic structure. (A) Three-dimensional schematic of the CFET-like geometry consisting of vertically stacked P-type and N-type silicon regions embedded within dielectric layers and supported on a substrate. The vertically stacked configuration provides multiple silicon–dielectric interfaces for investigating optical confinement in transistor-inspired nanoscale structures. (B) Normalized electric-field distribution inside the CFET-like structure, showing strong optical field localization near the silicon–dielectric interfaces of both stacked regions. The field profile confirms efficient redistribution of electromagnetic energy within the vertically integrated structure and demonstrates the possibility of achieving nanophotonic confinement in CMOS-compatible CFET-like architectures.

‘‘‘

the confinement behavior of light in vertically stacked transistor configurations. Since CFET integrates both N-type and P-type channels into a compact three-dimensional stacked structure, it provides an interesting platform for analyzing light propagation and electromagnetic energy localization within multiple active regions simultaneously. Figure 3.3.4(A) shows the structural arrangement of the CFET-like configuration, where vertically stacked silicon regions are embedded within dielectric

layers and supported on a substrate. The optical field propagating through the structure experiences strong interaction with the silicon–dielectric interfaces due to the high refractive-index contrast present within the device geometry. This interaction gradually redistributes the optical energy and enables confinement inside the active regions of the structure.

The normalized electric-field profile shown in Fig. 3.3.4(B) demonstrates that optical energy becomes localized within both stacked regions of the CFET-like structure. Strong field concentration is observed near the silicon–dielectric interfaces, indicating efficient confinement of electromagnetic energy in both transistor layers simultaneously. The field intensity distribution confirms that the stacked architecture supports efficient localization of optical energy within nanoscale dimensions.

Furthermore, the observed confinement behavior indicates gradual compression of the propagating optical mode into a smaller effective modal volume. As the modal dimensions decrease, the electromagnetic energy density increases within the confined regions, resulting in stronger field localization. Such concentration of optical energy enhances light–matter interaction and improves the capability of manipulating light at dimensions below the diffraction limit. The confinement characteristics observed in the proposed structure resemble plasmonic-like behavior where optical energy becomes concentrated within deeply subwavelength dimensions. However, unlike conventional plasmonic structures involving metallic propagation mechanisms and associated Ohmic losses, strong confinement here is achieved through dielectric mode engineering and geometrical optimization. Consequently, enhanced field localization is achieved while maintaining comparatively lower propagation losses. The strong localization of optical energy observed within the stacked CFET-like architecture demonstrates the potential of integrating nanophotonic functionality with future transistor structures. Such confinement characteristics can be highly advantageous for applications involving nanoscale optical sensing, optoelectronic coupling, enhanced light–matter interaction, nonlinear optical devices, and CMOS-compatible photonic integrated circuits.

3.3.5 Modal Purity, Coupling Efficiency, and Effective Refractive-Index Analysis

The modal characteristics of the proposed hollow taper structure were investigated through analysis of mode purity, coupling efficiency, and effective refractive-index variation under different operating conditions. Figure **??**a) illustrates the variation of mode purity as a function of the number of guided modes for different operating wavelengths ranging from 1400 nm to 1600 nm.

From Fig. 3.4(a), it is observed that the modal purity strongly depends on both the operating wavelength and the guided-mode distribution inside the hollow taper structure. At shorter wavelengths, the propagating optical field exhibits comparatively weaker confinement and reduced modal stability due to increased spreading of the electromagnetic field inside the silicon region. Consequently, the optical mode experiences partial coupling into higher-order guided modes, resulting in reduced mode purity.

As the operating wavelength approaches the telecommunication wavelength of 1550 nm, stronger localization of the optical field inside the hollow-core region is observed. The enhanced dielectric confinement improves the overlap between the fundamental propagating mode and the hollow taper geometry, thereby suppressing higher-order mode excitation and improving modal stability. The smoother variation in mode purity confirms efficient adiabatic mode evolution inside the taper structure.

Figure 3.4(b) illustrates the variation of coupling efficiency with taper length for different refractive-index values of the filled material inside the hollow-core region. The coupling efficiency exhibits periodic oscillatory behavior along the taper length due to modal interference and propagation phase variation between the confined optical modes. At lower refractive-index values, the optical field remains relatively weakly confined, leading to larger modal spreading and reduced transmission efficiency.

As the refractive index increases from 1 to 2, stronger optical confinement is achieved inside the hollow region due to enhanced refractive-index contrast between

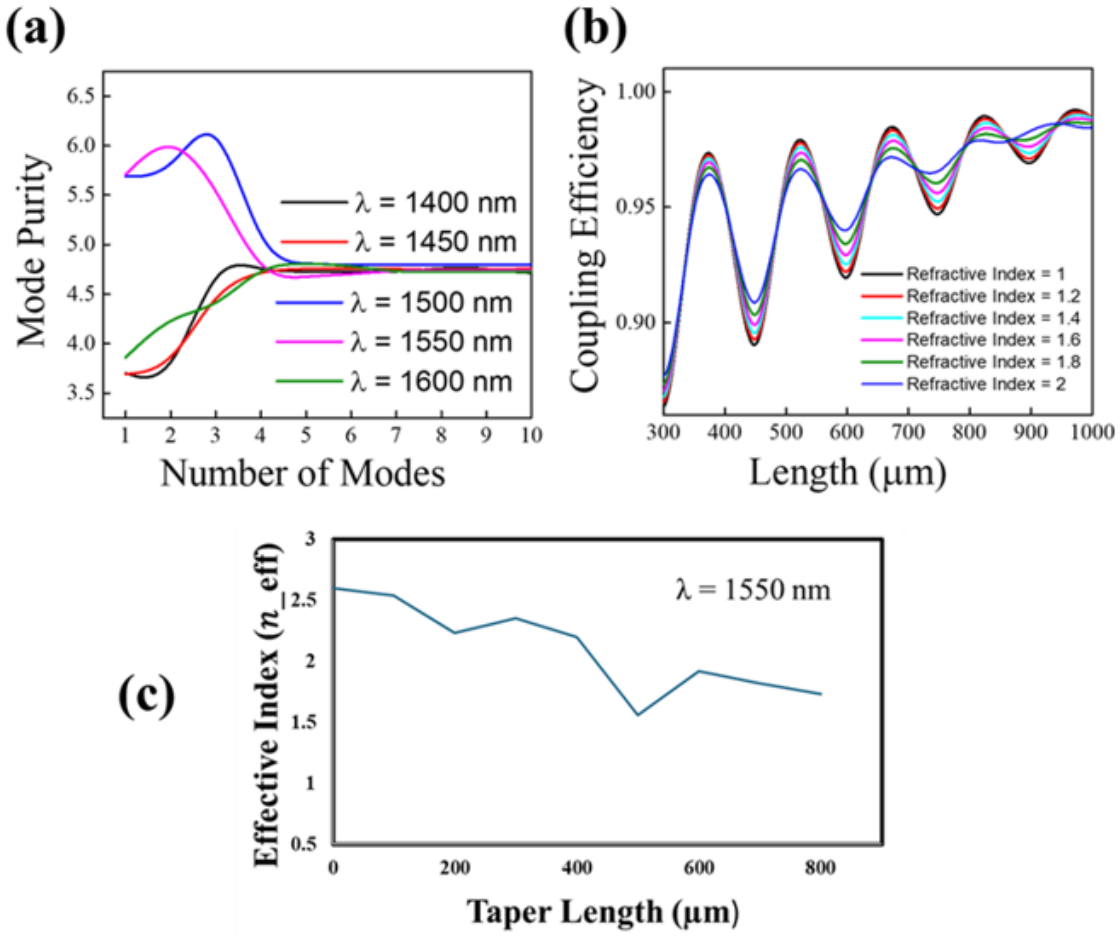


Figure 3.4: Modal purity, coupling efficiency, and effective refractive-index analysis of the proposed hollow 2-D taper coupler. (a) Variation of mode purity with respect to the number of guided modes at the output of the hollow 2-D tapered coupler for different input wavelengths. The plot indicates the stability of the fundamental output mode and the suppression of unwanted higher-order mode excitation. (b) Variation of coupling efficiency with taper length for different hollow-core filling materials having different refractive indices. In this analysis, the silicon thickness at the plasmonic-like output end is fixed at $t_p = 150\,\text{nm}$, while the gap width and gap thickness are fixed at $w_p = 300\,\text{nm}$ and $g_p = 30\,\text{nm}$, respectively. (c) Variation of effective refractive index as a function of hollow taper length at an operating wavelength of 1550 nm, showing gradual modal redistribution and confirming smooth adiabatic evolution along the taper.

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silicon and the surrounding medium. The improved confinement increases modal overlap between the propagating modes and reduces scattering losses, resulting in enhanced coupling efficiency. The oscillatory response gradually stabilizes at larger taper lengths, confirming improved propagation stability and near-adiabatic mode transformation.

Above figure shows the variation of effective refractive index (n_{eff}) along the taper length at an operating wavelength of 1550 nm. The effective refractive index decreases progressively as the taper length increases due to gradual redistribution of the electromagnetic field from the high-index silicon region toward the low-index hollow-core region.

Initially, the optical mode remains predominantly confined inside silicon, resulting in a relatively higher effective refractive index. However, as the taper dimensions decrease along the propagation direction, the optical field undergoes strong dielectric mode squeezing and shifts toward the hollow air region. This transition reduces the overall modal index and confirms smooth adiabatic evolution of the propagating optical mode inside the taper structure.

The observed effective-index variation further validates the ability of the proposed hollow taper configuration to support efficient subwavelength confinement while maintaining stable optical propagation characteristics.

3.3.6 Influence of Gap Width and Silicon Thickness on Coupling Characteristics

The influence of hollow-core gap width and silicon thickness on coupling efficiency was systematically investigated to evaluate the confinement characteristics of the proposed taper structure. Figure 3.4(a) illustrates the variation of coupling efficiency as a function of hollow-core gap width for different silicon thicknesses at the optical side of the taper structure.

The results reveal a strong dependence of coupling efficiency on both the gap width and silicon thickness. For lower silicon thickness values (t_o = 1–2 μm), the

coupling efficiency initially remains high but exhibits significant fluctuations and a gradual reduction as the gap width increases. This behavior occurs because thinner silicon layers provide weaker dielectric confinement, causing the optical mode to spread into the surrounding region and increasing radiation losses. In particular, for $t_o = 1\,\mu m$, the coupling efficiency shows noticeable oscillatory behavior with increasing gap width, indicating mode mismatch and unstable field confinement within the hollow region.

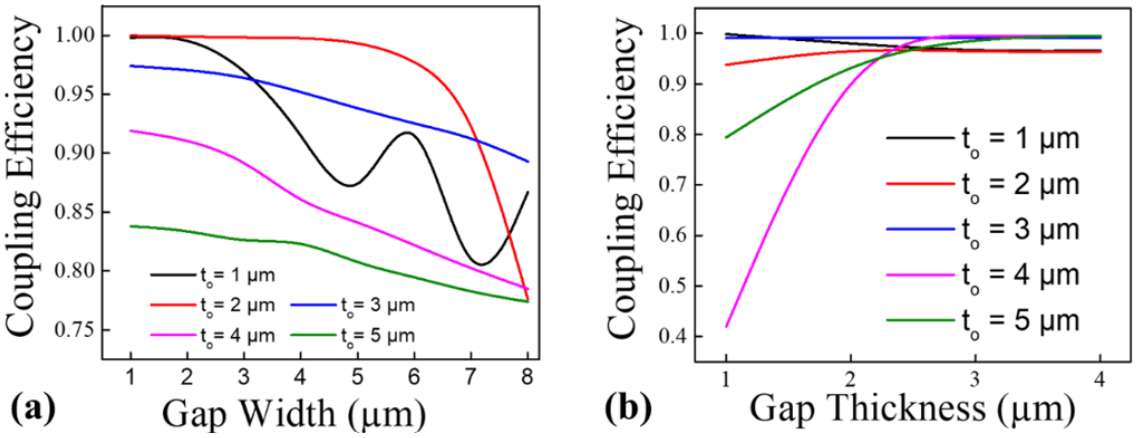


Figure 3.5: Influence of hollow-core gap dimensions and silicon thickness on the coupling efficiency of the proposed hollow 2-D taper coupler. (a) Variation of coupling efficiency with hollow-core gap width for different silicon thicknesses at the optical input side of the taper structure. This plot illustrates how the input-side gap width affects the modal overlap between the weakly confined photonic input mode and the taper-guided mode. (b) Variation of coupling efficiency with gap thickness for different silicon thicknesses at the plasmonic-like output side of the taper structure. This plot shows that proper optimization of the nanoscale gap thickness improves optical confinement near the silicon–air interface, enhances modal matching, and supports efficient power transfer toward the strongly confined output mode.

For larger silicon thickness values ($t_o = 3$–$5\,\mu m$), the coupling efficiency demonstrates more stable characteristics and remains comparatively higher over a broad range of gap widths. Thicker silicon layers enhance refractive-index contrast and

provide stronger confinement of the propagating mode, leading to better modal overlap and reduced scattering losses. However, when the gap width becomes excessively large, a gradual reduction in coupling efficiency is observed for all cases. This decrease can be attributed to expansion of the optical mode area, resulting in weaker localization of the electromagnetic field and reduced transmission efficiency.

Figure 3.5 (b) presents the variation of coupling efficiency with gap thickness at the plasmonic-like side of the taper structure. The results indicate that coupling efficiency increases rapidly with increasing gap thickness, particularly for smaller silicon thicknesses. For example, in the case of $t_o = 4\,\mu m$, the coupling efficiency increases sharply from approximately 0.45 to nearly unity as the gap thickness increases. This trend suggests that increasing the hollow-core gap thickness initially improves mode confinement and facilitates stronger field compression near the silicon–air interfaces.As the gap thickness continues to increase, the coupling efficiency gradually approaches saturation for all silicon thicknesses and remains close to unity. The saturation behavior indicates that beyond a certain thickness, further increase in the gap dimension no longer significantly improves mode matching because the optical field has already achieved efficient confinement within the structure. Additionally, larger silicon thicknesses exhibit smoother variations and achieve saturation more rapidly, confirming that stronger dielectric confinement enhances the robustness of the coupling process.

Overall, the results demonstrate that efficient operation of the proposed hollow taper requires careful optimization of both silicon thickness and hollow-core dimensions. Appropriate selection of these parameters ensures strong electromagnetic confinement, improved mode matching, and high coupling efficiency for photonic-to-plasmonic mode transformation.

3.3.7 Influence of Taper Length on Adiabatic Mode Evolution

The influence of taper length on optical confinement and coupling efficiency was investigated for different silicon thicknesses of the hollow taper structure. Figure 3.6(a) illustrates the variation of coupling efficiency with taper length for silicon thicknesses ranging from 1 µm to 5 µm.The simulation results indicate that coupling efficiency strongly depends on the taper length and the geometrical transition profile of the structure. For shorter taper lengths, abrupt changes in waveguide dimensions introduce significant modal perturbations, scattering losses, and partial radiation of optical power. As a result, coupling efficiency initially exhibits rapid oscillatory behavior and lower transmission characteristics. For larger silicon thickness values (t_o = 3–5 μm), the coupling efficiency increases more smoothly and reaches higher values comparatively faster due to stronger dielectric confinement and improved modal overlap. Stronger confinement reduces optical leakage and enhances stable propagation through the taper structure.

The oscillatory behavior observed at shorter taper lengths gradually diminishes as the taper becomes longer, indicating stabilization of the propagating optical mode and improved adiabaticity of the structure. Beyond taper lengths of approximately 3000–4000 µm, the coupling efficiency curves begin to approach saturation and remain close to unity. This saturation behavior indicates that beyond an optimum taper length, further increase in taper dimensions does not provide significant improvement in coupling performance because efficient mode conversion has already been achieved.

The results confirm that longer taper structures improve optical confinement and enable efficient transfer of optical energy into the nanoscale hollow-core region. However, excessively long taper structures may increase device footprint without providing considerable additional performance enhancement. Therefore, an optimized taper length should be selected to achieve a balance between high coupling efficiency, compact device size, and efficient adiabatic mode transformation.The oscillations observed at smaller taper lengths indicate repeated energy exchange between guided

and radiation modes caused by non-adiabatic mode evolution.

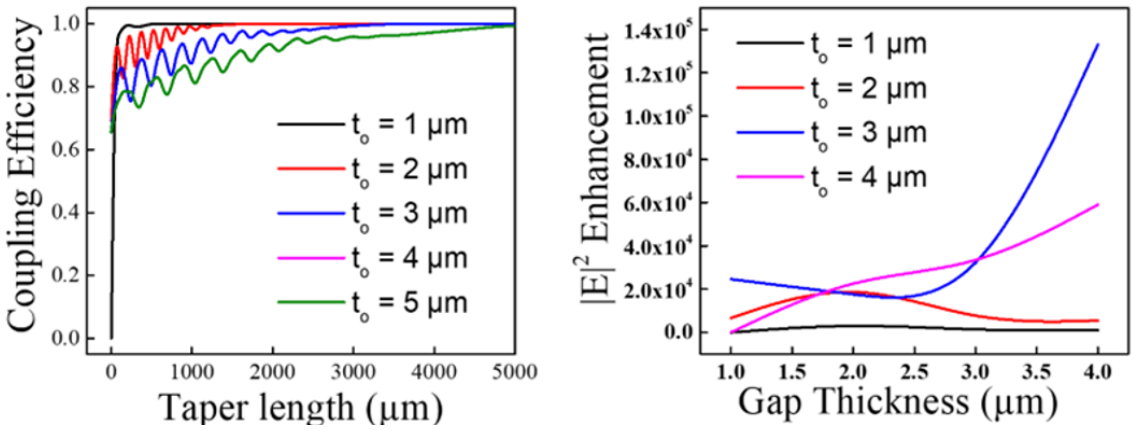


Figure 3.6: Influence of taper length, silicon thickness, and nanoscale gap thickness on the optical performance of the proposed hollow 2-D taper coupler. (a) Variation of coupling efficiency with taper length for different silicon thicknesses. This plot shows how the taper length controls the adiabaticity of mode transformation from the weakly confined photonic input mode to the strongly confined plasmonic-like output mode. Longer taper lengths provide smoother mode evolution and reduce non-adiabatic scattering, whereas shorter taper lengths may lead to stronger oscillations in coupling efficiency due to incomplete mode conversion. (b) Electric-field enhancement variation with gap thickness for different silicon thicknesses at the plasmonic-like output side of the taper structure. This plot demonstrates that the nanoscale gap thickness strongly influences optical field localization near the silicon–air interface, and proper optimization of silicon thickness and gap thickness enables enhanced light–matter interaction and strong subwavelength confinement.

For thinner silicon layers (t_o = 1–2 μm), strong oscillations are observed at shorter taper lengths before gradually stabilizing. This behavior can be attributed to weaker optical confinement, where the propagating field spreads over a larger region and becomes more sensitive to geometrical variations. In contrast, thicker silicon layers (t_o = 3–5 μm) show comparatively smoother variations and achieve higher coupling efficiency more rapidly due to stronger dielectric confinement and improved

modal overlap.As the taper length increases, smoother geometrical transitions enable gradual adiabatic evolution of the propagating optical mode. The optical field continuously adapts to the changing waveguide dimensions without exciting higher-order modes or generating strong reflections. Consequently, coupling efficiency progressively increases and approaches near-unity values for all silicon thicknesses. Beyond approximately 3000–4000 µm taper length, the curves exhibit saturation behavior, indicating that further increase in taper length provides only marginal improvement in coupling performance.

Figure 3.6(b) illustrates the variation of effective refractive index as a function of gap thickness for different silicon thicknesses. The results demonstrate that the effective index changes significantly with increasing gap thickness and depends strongly on the silicon layer dimensions. For smaller silicon thicknesses, the effective index exhibits relatively gradual variation, indicating weaker mode confinement and reduced interaction between the optical field and surrounding dielectric regions.

For larger silicon thicknesses, particularly for $t_o = 3\ \mu m$ and $t_o = 4\ \mu m$, a substantial increase in effective refractive index is observed at larger gap thickness values. This increase suggests stronger localization of the electromagnetic field and enhanced optical confinement within the taper structure. The sharp increase in effective index at larger gap dimensions indicates stronger field compression and transition toward highly confined plasmonic-like modes.

Overall, the results confirm that longer taper structures facilitate smooth adiabatic mode evolution and reduce scattering losses, while the effective refractive index variation provides insight into field localization and confinement characteristics within the proposed hollow taper structure. Appropriate optimization of taper length and structural dimensions therefore plays an essential role in achieving efficient optical coupling and high transmission performance.

3.3.8 Localized Electric-Field Enhancement and Subwavelength Confinement

The electric-field enhancement characteristics of the proposed hollow taper structure were analyzed as a function of gap thickness and silicon thickness. Figure 3.6(b) illustrates the variation of electric-field enhancement with gap thickness for different silicon thickness values at the plasmonic-like side of the taper structure.

The results demonstrate substantial enhancement of the localized electric field inside the hollow-core region due to strong dielectric mode squeezing and subwavelength confinement. The field enhancement exhibits a strong dependence on both gap thickness and silicon thickness, indicating that geometrical parameters significantly influence the concentration of electromagnetic energy within the taper structure.

For smaller silicon thickness values (t_o = 1–2 μm), the electric-field enhancement remains relatively low and exhibits only gradual variation with increasing gap thickness. This behavior can be attributed to weaker dielectric confinement, which allows a larger portion of the optical field to spread into the surrounding region, thereby reducing the localized energy density inside the hollow region.

In contrast, for larger silicon thicknesses (t_o = 3–4 μm), a substantial increase in electric-field enhancement is observed as the gap thickness increases. Particularly for $t_o = 3\ \mu m$, the enhancement remains nearly constant at lower gap thickness values and then increases sharply beyond approximately 3 μm, reaching significantly larger values compared to other thicknesses. This behavior suggests stronger localization of the optical field and increased electromagnetic energy concentration near the silicon–air interface.

The rapid increase in field enhancement at larger gap thickness values can be explained by improved dielectric confinement and stronger mode compression inside the hollow-core region. As the optical mode becomes more tightly confined, the effective modal volume decreases, leading to an increase in local electromagnetic energy density. The resulting concentration of optical energy produces strong field localization within a nanoscale region.

The electric-field enhancement inside the taper structure is expressed as

$$|E|^2_{\text{enhancement}} = \frac{|E_{\text{localized}}|^2}{|E_{\text{input}}|^2} \tag{3.2}$$

where $E_{\text{localized}}$ represents the localized electric-field intensity near the taper output and E_{input} denotes the input optical-field amplitude.

The strong localization of electromagnetic energy achieved inside the hollow region resembles hybrid plasmonic confinement behavior. However, unlike conventional metal-based plasmonic structures, the proposed dielectric taper configuration achieves strong confinement without introducing Ohmic absorption losses. This indicates that the proposed structure combines the advantages of strong field localization and reduced propagation loss. Such enhanced field confinement is highly beneficial for applications involving nonlinear optics, nanophotonic sensing, optical trapping, and enhanced light–matter interaction.

3.3.9 Wavelength-Dependent Optical Response and Confinement Behavior

The wavelength-dependent optical response of the proposed hollow taper structure was investigated to analyze the variation of electric-field enhancement and coupling efficiency within the telecommunication wavelength range. Figure 3.7(a) illustrates the variation of electric-field enhancement with operating wavelength for different hollow-core gap widths.The results demonstrate that electric-field enhancement strongly depends on both the operating wavelength and the hollow-core dimensions. Significant variations in field localization are observed due to wavelength-dependent changes in optical confinement and modal interaction within the taper structure.

For smaller gap widths (g_o = 1–3 μm), the electric-field enhancement remains relatively low and exhibits only gradual variation over the considered wavelength range. This behavior indicates weaker localization of the electromagnetic field and reduced concentration of optical energy within the hollow-core region. The optical mode remains distributed over a larger effective modal volume, resulting in lower

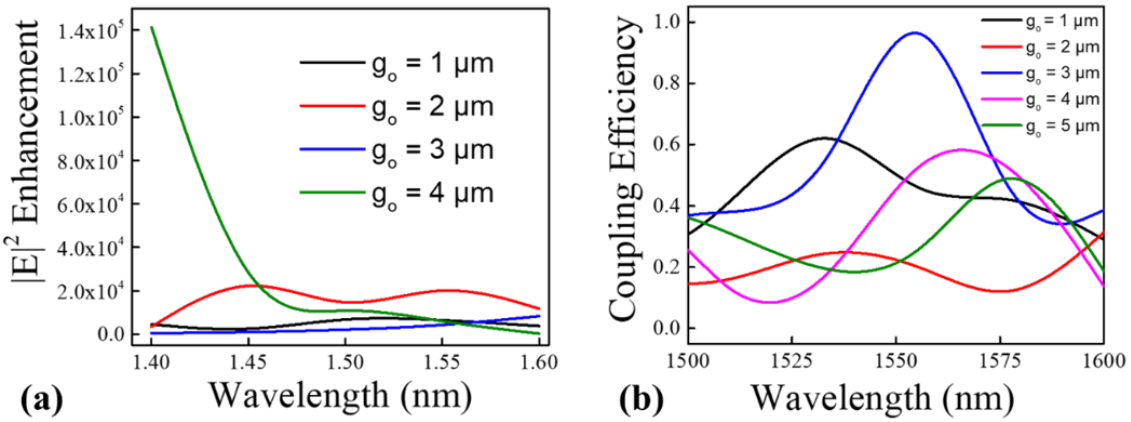


Figure 3.7: Wavelength-dependent electric-field enhancement and coupling efficiency of the proposed hollow 2-D taper coupler for different hollow-core gap widths. (a) Variation of electric-field enhancement with operating wavelength for different hollow-core gap widths. This plot shows how the operating wavelength and gap width influence the localization of the optical field near the silicon–air interface at the plasmonic-like output region. The variation in field enhancement indicates the wavelength-dependent confinement behavior of the proposed taper structure. (b) Variation of coupling efficiency with operating wavelength for different hollow-core gap widths. This plot demonstrates the effect of wavelength and hollow-core geometry on optical power transfer through the taper. The results confirm that proper optimization of the hollow-core gap width supports efficient coupling and strong field confinement near the telecommunication wavelength region.

field intensity enhancement.

In contrast, for a larger gap width of $g_o = 4\ \mu m$, substantially stronger field enhancement is observed, particularly in the lower wavelength region around 1400–1450 nm. The electric-field enhancement reaches its maximum value in this region and then decreases rapidly with increasing wavelength. This behavior can be attributed to stronger optical mode compression and enhanced refractive-index contrast, leading to efficient concentration of electromagnetic energy near the silicon–air interface. As the wavelength increases, the optical field gradually expands, reducing confinement strength and causing a decrease in localized field intensity.

Figure 3.7(b) illustrates the variation of coupling efficiency with operating wavelength for different hollow-core dimensions. The coupling efficiency exhibits a strong wavelength dependence and shows distinct resonance-like peaks associated with wavelength-dependent modal interaction and phase matching inside the taper structure.For different gap widths, the coupling efficiency reaches maximum values at different operating wavelengths, indicating that geometrical dimensions strongly influence mode matching conditions. In particular, the structure with $g_o = 3\ \mu m$ exhibits the highest coupling efficiency near the wavelength range of approximately 1550–1560 nm, where the coupling efficiency approaches nearly unity. This indicates optimized overlap between the propagating dielectric mode and the confined mode inside the hollow taper structure. The oscillatory behavior observed in the coupling efficiency curves results from wavelength-dependent effective refractive-index variation and interference between propagating optical modes. Away from the optimum wavelength region, a gradual reduction in coupling efficiency is observed due to increased mode mismatch and weaker confinement characteristics.

Overall, the proposed hollow taper coupler demonstrates optimized optical performance near the standard telecommunication wavelength of 1550 nm, where efficient mode transformation, strong field localization, and high coupling efficiency are simultaneously achieved. The stable wavelength response confirms the suitability of the proposed taper structure for integrated optical communication systems, nanophotonic sensing applications, and compact photonic integrated circuits operating within the telecommunication band.

Chapter 4

Conclusion and Future Scope

4.1 Conclusion

This thesis presents a detailed design and numerical investigation of a CMOS-compatible hollow 2-D taper coupler cum mode transformer, developed to address one of the most fundamental challenges in integrated photonics: the efficient transfer of optical energy between conventional photonic waveguides and deeply subwavelength nanophotonic or plasmonic-scale structures. The primary limitation in such systems arises from the severe mismatch in mode size, effective index, and confinement characteristics between micron-scale optical modes and nanoscale guided modes. Overcoming this mismatch in a compact, low-loss, and fabrication-compatible manner is critical for enabling high-density photonic integration.

To address this, the proposed structure introduces a dual-axis tapered silicon–air geometry in which both the lateral width and vertical thickness are gradually reduced along the propagation direction. This two-dimensional tapering enables controlled and adiabatic evolution of the optical mode, allowing it to transition smoothly from a weakly confined photonic mode at the input to a strongly confined plasmonic-like mode at the output. Unlike conventional plasmonic devices, where field confinement is achieved through metal–dielectric interfaces at the cost of significant Ohmic losses, the present approach relies entirely on dielectric confinement and high index contrast at the silicon–air interface. As a result, plasmonic-like field localization is achieved without introducing absorption losses, thereby maintaining efficient power transmission.

The physical mechanism underlying this transformation is governed by gradual mode compression and redistribution of the electromagnetic field as the taper narrows. At the input, the optical mode is predominantly confined within the high-index silicon region. As the taper progresses, the effective modal cross-section decreases, forcing the optical field to expand and redistribute into the hollow air region. This leads to strong localization of the electric field at the silicon–air interface, resulting in subwavelength confinement and significant enhancement of field intensity. This behavior closely resembles hybrid plasmonic modes, although it is achieved purely

through dielectric structuring rather than free-electron oscillations.

Comprehensive numerical analysis using Eigenmode Expansion and Finite-Difference Time-Domain methods confirms the effectiveness of the proposed design. The results demonstrate near-unity normalized coupling efficiency, indicating efficient power transfer from the input photonic mode to the output confined mode. High mode purity is observed across the structure, ensuring that the majority of the optical power remains in the desired fundamental mode with minimal excitation of higher-order modes. Additionally, strong electric-field enhancement at the output confirms the ability of the taper to concentrate optical energy within a nanoscale region, which is particularly beneficial for applications involving enhanced light–matter interaction.

The device exhibits optimal performance at the 1550 nm telecommunications wavelength, where the interplay between material dispersion, geometric scaling, and mode confinement leads to an efficient balance between transmission and localization. The wavelength-dependent analysis further highlights the sensitivity of the device to phase matching and modal dispersion, emphasizing the importance of geometry-controlled design for achieving peak performance.

A systematic parametric study has been carried out to evaluate the influence of key design parameters, including taper length, silicon thickness, hollow gap dimensions, and refractive index variation within the core region. The results reveal that taper length plays a crucial role in ensuring adiabatic mode evolution, with longer tapers promoting smoother transitions and reduced radiation losses until a saturation regime is reached. Similarly, the silicon thickness and gap dimensions govern the effective index contrast and modal overlap, directly impacting coupling efficiency and field enhancement. The ability to tune these parameters provides valuable design flexibility, enabling optimization for specific applications and operating conditions.

When compared with existing coupling strategies such as inverse taper couplers, grating couplers, and hybrid plasmonic devices, the proposed hollow 2-D taper demonstrates a superior balance between performance metrics. Inverse tapers, while efficient, typically require longer device lengths and precise alignment. Grating

couplers offer compactness but suffer from diffraction losses and limited bandwidth. Hybrid plasmonic couplers achieve strong confinement but are inherently limited by metal-induced losses and fabrication complexity. In contrast, the present design achieves high coupling efficiency within a compact footprint (20 µm), avoids metal-related losses, and remains fully compatible with standard CMOS fabrication processes, making it a highly practical and scalable solution.

Beyond performance, the structural simplicity and fabrication feasibility of the proposed device further strengthen its applicability. The design is implemented on a silicon-on-insulator (SOI) platform and relies on well-established fabrication techniques such as deep-UV or electron-beam lithography and anisotropic etching to achieve nanoscale features. The absence of metallic components simplifies the fabrication process and improves device reliability, while the sub-50 nm hollow region remains within the capabilities of advanced nanofabrication technologies.

Overall, this work establishes a physically robust and technologically viable framework for achieving efficient mode transformation between photonic and plasmonic-like regimes on a silicon platform. The proposed hollow 2-D taper not only addresses the fundamental challenge of mode mismatch but also provides a versatile interface for enabling strong field confinement, efficient coupling, and compact device integration.

Despite the promising results demonstrated through numerical simulations, several avenues remain open for future exploration. Experimental fabrication and characterization of the proposed structure will be essential to validate its real-world performance and assess the impact of fabrication tolerances, surface roughness, and material imperfections. Further improvements can be achieved through material optimization, such as introducing engineered dielectric fillings within the hollow core to enhance confinement or enable active tunability. Integration with active photonic components, including modulators, detectors, and light sources, can lead to the development of fully functional on-chip systems for communication, sensing, and quantum photonics applications.

Additionally, extending the design toward broadband and multi-wavelength operation represents an important direction for enabling applications in wavelength-

division multiplexing and spectroscopy. Hybrid integration with advanced photonic structures, such as metasurfaces or photonic crystals, may further enhance device functionality and enable new mechanisms for light manipulation at the nanoscale.

In conclusion, the hollow 2-D taper coupler presented in this thesis provides a scalable, efficient, and CMOS-compatible solution for bridging the gap between conventional photonic systems and nanoscale optical devices. By enabling low-loss, high-efficiency, and compact mode transformation, this work contributes a significant step toward the realization of next-generation integrated photonic and nanophotonic technologies.

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4.2 Fabrication Challenges and Experimental Realization

Although the present work is primarily based on numerical simulation, the proposed hollow 2-D taper coupler cum mode transformer has been designed by considering CMOS-compatible material platforms and practical nanofabrication requirements. The structure is based on silicon and air as the guiding and hollow regions, respectively, which makes it suitable for possible realization using silicon photonics fabrication processes. A possible experimental realization of the proposed device may be carried out on a silicon-on-insulator (SOI) wafer or a silicon substrate by defining the taper geometry using high-resolution lithography followed by controlled dry etching. The fabrication process may begin with the deposition or selection of a silicon device layer with the desired thickness. The two-dimensional taper profile can then be patterned using electron-beam lithography or deep ultraviolet lithography, depending on the required feature size and fabrication facility. After lithographic patterning, the silicon region can be etched using reactive-ion etching (RIE) or inductively coupled plasma reactive-ion etching (ICP-RIE) to transfer the taper profile into the silicon layer. Since the

proposed device contains a hollow air region, the formation of the hollow core is one of the most critical fabrication steps. This region may be realized through sacrificial layer deposition and selective removal, controlled isotropic etching, or wafer-bonding-based techniques. The final process flow must ensure that the air gap remains well-defined along the taper length without collapse or unwanted deformation. The major fabrication challenge in the proposed hollow taper structure is the accurate control of nanoscale geometrical parameters, especially the hollow-core gap width, gap thickness, silicon thickness, and taper profile. Since the device operation depends on adiabatic mode transformation, any abrupt variation in the taper geometry may disturb the smooth evolution of the optical mode. Non-uniform tapering can lead to scattering loss, reflection, and excitation of higher-order modes. Therefore, maintaining a smooth sidewall profile along both the lateral and vertical tapering directions is essential for achieving high coupling efficiency and strong field confinement. Another important challenge is sidewall roughness introduced during the etching process. Surface roughness at the silicon–air interface can scatter the confined optical field and reduce the mode purity of the transmitted signal. This effect becomes more significant near the narrow output region of the taper, where the optical field is strongly localized close to the silicon–air interface. Therefore, optimized etching conditions, appropriate hard-mask selection, and post-etch smoothing techniques may be required to minimize roughness-induced scattering loss. Dimensional tolerance is also a critical aspect of the proposed design. Variations in the hollow-core gap width can affect the modal overlap between the input optical mode and the taper-guided mode. If the gap width becomes too large, the optical mode may expand and reduce the coupling efficiency. On the other hand, if the gap width becomes too small, the mode may become highly confined and mismatched with the input photonic mode. Similarly, variation in the output-side gap thickness directly influences electric-field enhancement and plasmonic-like confinement. A very small gap thickness may improve field localization but can be difficult to fabricate accurately, while a larger gap thickness may reduce the degree of confinement after a certain limit. Hence,

careful optimization of the hollow-core dimensions is required to balance coupling efficiency, field enhancement, and fabrication feasibility. The silicon thickness also plays an important role in determining the confinement strength and propagation stability. Thinner silicon regions may lead to weaker confinement and larger sensitivity to fabrication variations, whereas thicker silicon regions provide improved modal stability but may increase the overall device size. The taper length must also be selected carefully. A shorter taper may reduce the device footprint but can introduce non-adiabatic transitions, whereas a longer taper improves mode evolution but increases the chip area. Therefore, the final fabricated device should be designed by considering the trade-off between compactness, adiabaticity, and fabrication tolerance. For experimental characterization, a tunable laser source operating near the telecommunication wavelength of 1550 nm can be used. Light may be coupled into the input side of the taper using a lensed fiber, edge-coupling setup, or an integrated input waveguide. The transmitted optical power can be measured at the output using an optical power meter, photodetector, or infrared camera. The coupling efficiency can be estimated by comparing the measured output power with the calibrated input power after accounting for fiber coupling and propagation losses. In addition, near-field optical imaging or mode-profile measurement may be used to verify the compression of the optical field and the formation of a strongly confined plasmonic-like mode near the taper output. The experimental results can then be compared with the simulated coupling efficiency, field enhancement, and mode evolution characteristics. Any deviation between simulation and experiment may arise due to fabrication imperfections such as sidewall roughness, gap variation, etch-depth error, alignment mismatch, or material non-uniformity. Therefore, a detailed tolerance analysis and fabrication-aware optimization will be important steps before practical device implementation. Overall, the proposed hollow 2-D taper coupler provides a promising route toward experimentally realizable fiber-to-chip and photonic-to-nanophotonic mode transformation. Although the present thesis focuses on simulation-based analysis, the use of silicon, air-gap engineering, and CMOS-compatible design principles makes the structure suitable for future

fabrication and experimental validation. With further process optimization, the proposed device can be integrated with silicon photonic circuits, nanoscale sensors, nonlinear photonic devices, and high-density on-chip optical interconnects.

Bibliography

1. M. I. Stockman, "Nanofocusing of optical energy in tapered plasmonic waveguides," *Phys. Rev. Lett.*, vol. 93, no. 13, p. 137404, Sep. 2004.

2. E. A. J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics," *Bell System Technical Journal*, vol. 48, no. 7, pp. 2071–2102, Sep. 1969.

3. C. Plamadeala et al., "Three-Dimensional Photonic Structures Fabricated by Two-Photon Polymerization for Microfluidics and Microneedles," *International Conference on Transparent Optical Networks*, 2018.

4. R. F. Oulton et al., "A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation," *Nature Photonics*, vol. 2, no. 8, pp. 496–500, Aug. 2008.

5. S. I. Bozhevolnyi et al., "Channel plasmon subwavelength waveguide components including interferometers and ring resonators," *Nature*, vol. 440, no. 7083, pp. 508–511, Mar. 2006.

6. H. Ditlbacher et al., "Silver nanowires as surface plasmon resonators," *Physical Review Letters*, vol. 95, no. 25, Dec. 2005.

7. A. A. Norrman et al., "Long-range higher-order surface-plasmon polaritons," *APS*, vol. 90, no. 5, Nov. 2014.

8. H. A. Atwater and A. Polman, "Plasmonics for improved photovoltaic devices," *Nature Materials*, vol. 9, no. 3, pp. 205–213, Mar. 2010.

9. S. Kumar et al., "Reconfigurable multiwavelength nanophotonic circuit based on a low-voltage, optically readable engineered resistive switch," *Nanoscale*, 2025.

10. M. Wood, P. Sun, and R. M. Reano, "Compact cantilever couplers for low-loss fiber coupling to silicon photonic integrated circuits," *Optics Express*, vol. 20, no. 1, p. 164, Jan. 2012.

11. J. A. Dionne et al., "Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization," *Phys. Rev. B*, vol. 73, no. 3, p. 035407, Jan. 2006.

12. J. Van Asch et al., "A methodical approach to design adiabatic waveguide couplers for heterogeneous integrated photonics," *Journal of Physics: Photonics*, vol. 6, no. 4, p. 045013, Sep. 2024.

13. G. Son et al., "High-efficiency broadband light coupling between optical fibers and photonic integrated circuits," *Nanophotonics*, vol. 7, no. 12, pp. 1845–1864, Dec. 2018.

14. X. Chen et al., "Apodized waveguide grating couplers for efficient coupling to optical fibers," *IEEE Photonics Technology Letters*, vol. 22, no. 15, pp. 1156–1158, 2010.

15. S. Kumar et al., "Multilevel Nanophotonic Resistive Switching in Ag-ITO-SiO_2 on Silicon with Enhanced Optical Storage Density," *Journal of Lightwave Technology*, 2024.

16. M. Asaduzzaman et al., "A compact silicon grating coupler based on hollow tapered spot-size converter," *Scientific Reports*, vol. 8, no. 1, pp. 1–9, Dec. 2018.

17. R. Dev Mishra et al., "Nanophotonic resistive switch based on tapered copper-silicon structure with low power and high extinction ratio," *Optics & Laser Technology*, vol. 175, p. 110833, Aug. 2024.

18. J. Tian et al., "Broadband high-efficiency surface-plasmon-polariton coupler with silicon-metal interface," *Applied Physics Letters*, vol. 95, no. 1, Jul. 2009.

19. D. Chelladurai et al., "Low-loss hybrid plasmonic coupler," *Optics Express*, vol. 27, no. 8, pp. 11862–11868, Apr. 2019.

20. Q. Li and Z. Zhang, "Bonding and Anti-bonding Modes of Plasmon Coupling Effects in TiO_2-Ag Core-shell Dimers," *Scientific Reports*, vol. 6, no. 1, pp. 1–7, Jan. 2016.

21. Y. Sui et al., "Long-range interference of localized electromagnetic field enhancement in plasmonic nanofinger lattices," *Frontiers in Physics*, vol. 10, p. 951944, Sep. 2022.

22. S. Kumar et al., "Numerical Analysis of Laterally and Vertically Coupled Hybrid Plasmonic Modes in Silicon Tip," *Plasmonics*, 2022.

23. "Wavelength Selective Coupler - Cables Unlimited Inc."

24. "PASSIVE OPTICAL COMPONENTS," *Electro-Optical Systems Design*, vol. 6, no. 11, 1974.

25. M. S. Ab-Rahman et al., "The characterization of FTTH wavelength selective coupler," *IEEE International Conference on Semiconductor Electronics*, pp. 302–305, 2008.

26. H. Tazawa et al., "Fiber-optic coupler based refractive index sensor and its application to biosensing," *Applied Physics Letters*, vol. 91, no. 11, Sep. 2007.

27. S. A. Maier, *Plasmonics: Fundamentals and Applications*, 2007.

28. M. E. Stewart et al., "Nanostructured plasmonic sensors," *Chemical Reviews*, vol. 108, no. 2, pp. 494–521, Feb. 2008.

29. M. Saeed et al., "Characteristics of hybrid surface plasmon polaritons at a chiral graphene metal interface in cylindrical waveguides," *Optics and Quantum Electronics*, vol. 53, no. 10, pp. 1–14, Oct. 2021.

30. S. Kumar et al., "Double-Slot Nanophotonic Platform for Optically Accessible Resistive Switching with High Extinction Ratio and High Endurance," *ACS Photonics*, vol. 10, no. 11, pp. 4071–4078, Nov. 2023.

31. L. Singh, S. Jain, and M. Kumar, "Electrically writable silicon nanophotonic resistive memory with inherent stochasticity," *Optics Letters*, vol. 44, no. 16, p. 4020, Aug. 2019.

32. G. Singh et al., "Generating Localized Plasmonic Fields on an Integrated Photonic Platform using Tapered Couplers for Biosensing Applications," *Scientific Reports*, vol. 7, no. 1, pp. 1–8, Nov. 2017.

33. R. Ameling and H. Giessen, "Microcavity plasmonics: Strong coupling of photonic cavities and plasmons," *Laser & Photonics Reviews*, vol. 7, no. 2, pp. 141–169, Mar. 2013.

34. G. V. Naik et al., "Alternative plasmonic materials: Beyond gold and silver," *Advanced Materials*, vol. 25, no. 24, pp. 3264–3294, Jun. 2013.

35. P. R. West et al., "Searching for better plasmonic materials," *Laser & Photonics Reviews*, vol. 4, no. 6, pp. 795–808, Nov. 2010.