Analysis of Tapered Optical Fiber for Filtering and Mode Transformation

M.Tech Thesis

By

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DISCIPLINE OF ELECTRICAL ENGINEERING

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A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Analysis of Tapered Optical fiber for filtering and Mode transformation** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF Electrical Engineering, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from August 2021 to June 2023 under the supervision of Mukesh Kumar, Professor, Indian Institute of Technology Indore.

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.

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

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Ankit Gangwar has successfully given his M.Tech. Oral Examination held on **11/05/2023.**

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Signature of PSPC Member #2
Date:

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ABSTRACT

The rapid growth of information technology is closely tied to the advancement of modern telecommunication systems. Optical fiber communication has emerged as a crucial element, enabling high-speed and high-quality communication systems. Today, optical fibers are used not only for telecommunications connections, but also for the Internet and local area networks (LANs), achieving high transmission speeds. However, optical signals in optical fibers often require manipulations such as filtering and mode transformation for number of reasons such as Bandwidth management, integrating different fiber types, conditioning of signal, multiplexing, and demultiplexing etc. The proposed device utilizes a tapered optical fiber for filtering and mode transformation. This design consists of two stages, where the first stage involves a tapered optical fiber ($R = 1\mu m$, $r = 0.5\mu m$, $L = 5\mu m$) that achieves 0.83 normalized power and a half-power bandwidth (HPBW) of $0.17\ \mu m$ at a wavelength of $1.44\ \mu m$. The second stage extends the first stage by adding a metal layer over the optical fiber, enabling the conversion of photonic to plasmonic mode. At the metal fiber interface, the coupling efficiency reaches 81.2%, showcasing a clear preference for silver as the optimal metal choice. This preference is based on its ability to maximize power transmission compared to other metals. However, the thickness of metal layer does not contribute to the mode conversions. The proposed device demonstrates excellent suitability for performing various operations and holds great potential for applications in photonic devices at the nanoscale. This concept opens doors to the development of other nano-scale functionalities such as optical modulators, optical switches, polarization converters, and more.

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ACRONYMS

SPP	Surface Plasmon Polariton
MOS	Metal Oxide Semiconductor
MIM	Metal Insulator Metal
IMI	Insulator Metal Insulator
HPW	Hybrid Plasmonic Waveguide
PIC	Photonic Integrated Circuit
FOM	Figure of Merit
WDM	Wavelength Division Multiplexing
SiO2	Silicon Dioxide
MRR	Micro Ring Resonator
ITO	Indium Tin Oxide
ENZ	Epsilon Near Zero
FDE	Finite Difference Eigenmode (FDE) solver

NOMENCLATURE

ϵ	Dielectric Constant
λ	Wavelength
ω	Angular Frequency
μ	Permeability Constant
$\hbar$	Reduced Planck's Constant
β	Propagation Constant
Φ	Phase Shift
EF	Fermi Energy Level
Ko	Free Space Wave Number
ω_p	Plasma Frequency
e	Charge of the Electron
ne	Electron Density
me	Effective mass of Electron
n_{eff}	Effective Refractive Index
L	Propagation Length
α	Transmission Coefficient
Q	Quality Factor
E	Electric Field Intensity
D	Density of States

Chapter 1
Introduction to Nanophotonics

1.1 Nanophotonics

Nanophotonics is a science and technology field focusing on the interaction between light and nanoscale structures. It involves manipulating and controlling light at the nanometer scale, where the size is often on the nanometer scale (one billionth of a meter) [1]. In nanophotonics, researchers study how light behaves and interacts with nanoscale materials and structures, including nanoparticles, nanowires, nanoantennas, and photonic crystals [2]. These structures are designed and manufactured to control the properties of light, such as its emission, propagation, and detection, in ways not possible with conventional optics. One of the key aspects of nanophotonics is their ability to limit light to extremely small volumes, allowing the discovery of phenomena occurring at the nanoscale. This light restriction can lead to enhanced interactions between light and matter, leading to a variety of applications [3]. Nanophotonics has the potential to revolutionize fields such as telecommunications, information processing, energy extraction, sensing, and biomedicine. Some specific areas of research and applications in nanophotonics include:

a) **Plasmonics:** The study of surface plasmons, which are collective vibrations of electrons in metal nanostructures. Plasmonics allows the control of light at sub-wavelength scales and finds applications in optical sensing, imaging, and data storage [4].

b) **Nanoscale light source:** Development of efficient nanoscale light sources, such as nano LEDs (nanoscale light emitting diodes) and nano lasers, have potential applications in optical communications and on-chip computing.

c) **Photonic crystals:** Design and fabrication of cyclic nanostructures that control the transmission of light as a function of its wavelength [5]. Photonic crystals can be used to create new integrated optics and light manipulation devices.

d) **Nano photovoltaics:** Using nanoscale materials and structures to improve light absorption and energy conversion efficiency in solar cells and other photovoltaic devices [6].

e) **Nanophotonic sensor:** Development of highly sensitive sensors based on the interaction of light with nanoscale materials, enabling applications in biosensors, environmental monitoring, and chemical sensors [7].

The field of nanophotonics is interdisciplinary, combining principles from physics, materials science, optics, electrical engineering, and chemistry. It involves both theoretical research and experimental techniques to fabricate and characterize nanoscale photonic structures.

1.2 Nanophotonic devices and applications

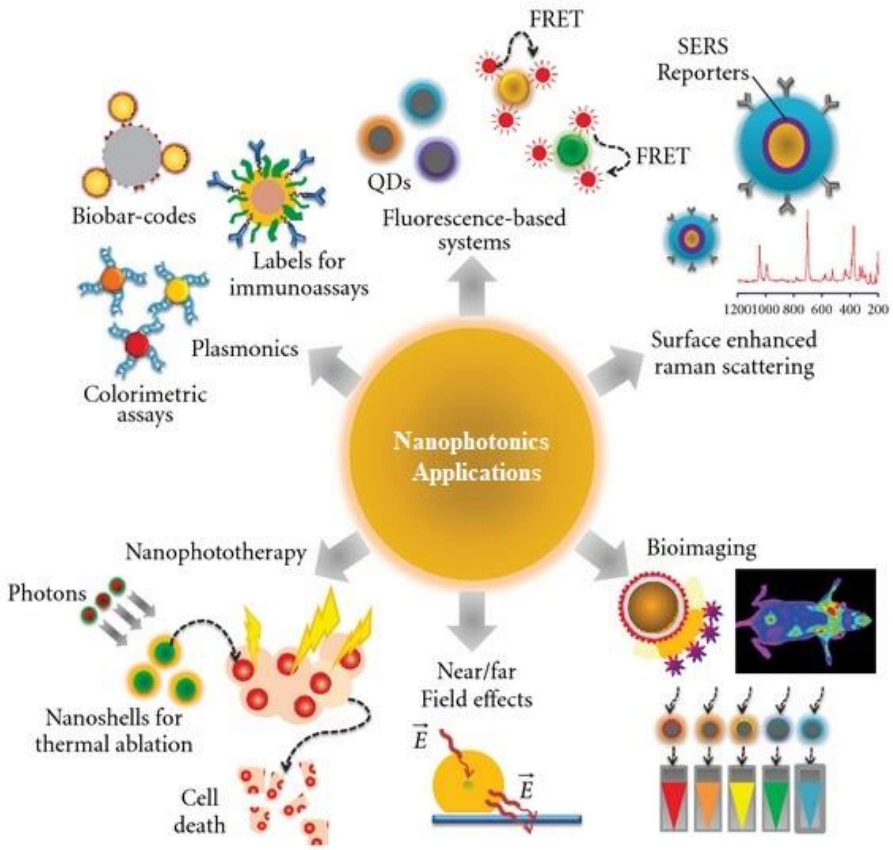

Figure 1.1 Nanophotonics Applications [7]

The ability to control light matter interaction at the scale of a fraction of a wavelength of light has given rise to the area of photonics commonly known as Nanophotonics [8]. The plasmons, slot waveguide, and photonic crystals are the few waveguides engineered device technologies that enable us to have devices much smaller than the dimensions of wavelength [2]. These devices have certain drawbacks like propagation losses and crosstalk due to leakage across the nano dimension device. Hybrid Plasmonic Waveguide (HPW) is proven to be a promising candidate in confining the light in deep subwavelength region and offering low propagation losses combining the properties of both Surface Plasmon Polariton (SPP) and photonic waveguides [9]. In nanophotonic devices, the light-matter interaction is large and larger the interaction, the easier it is to control and make better functional devices with high efficiency. The devices like optical switches, interconnects, modulators, polarization controllers, and memory are the few examples of such controlling and manipulating of the light using nanophotonic devices [2]. Nanophotonic devices finds applications in almost all the fields but not limited to data centers, quantum computing, aeronautics, defense, biosensors, and telecommunications [7].

1.2.1 Fiber Optic Devices

Fiber optic devices are devices that utilize optical fibers to transmit and manipulate light signals fiber for various applications. Optical fibers are thin, flexible, transparent strands of glass or plastic that can transmit light over long distances with minimal loss and distortion [10]. Fiber optic devices take advantage of the unique properties of optical fiber to enable high-speed, high-capacity data transmission, sensing, and other optical functions. Here are some common types of fiber optic devices:

1.2.1.1 Tapered Optical fiber

A tapered optical fiber refers to an optical fiber whose diameter gradually decreases over a given length. Tapering can be achieved by various techniques such as fiber stretching or etching [11]. Tapered optical fibers have unique optical properties that make them useful in a wide variety of applications. Here are some important aspects of tapered optical fibers.

Mode conversion: Tapered fibers allow efficient mode conversion between different optical modes. As the fiber diameter decreases along the taper, so does the mode field diameter [12]. This mode-field diameter change enables the conversion of light from one mode to another, e.g., from a higher-order mode to a single mode or vice versa. This property is especially important in communications and fiber optic sensing applications.

Light inclusions: Tapered fibers can provide better optical confinement compared to regular fibers [13]. As the fiber diameter decreases, the evanescent field outside the core becomes stronger, allowing efficient interaction with surrounding materials or analytes. This property is exploited in applications such as evanescent wave detection, where the evanescent field interacts with the external environment, enabling detection of refractive index changes and surface binding events [14].

Optical coupling: Tapered fibers can be used for efficient optical coupling between different optical components. By taping the fiber, the mode field diameter can be matched to the dimensions of other optical elements and devices, enabling efficient light transmission. This is especially useful in integrated photonics and fiber waveguide coupling applications [15].

Nonlinear optics: Tapered fibers can exhibit enhanced optical nonlinear effects due to the confinement of high light intensity in small diameter regions. This property is exploited in applications such as supercontinuum generation, frequency conversion, and nonlinear microscopy.

Tapered optical fibers offer versatility and flexibility in tailoring the optical properties of light propagation. They have applications in telecommunications, fiber sensing, biophotonics, quantum optics, and various other fields where efficient manipulation and control of light is desired [16].

Tapered optical fibers are good candidates for manipulating and controlling light as they enhance the evanescent field exposed to the surroundings and increase penetration depth. Taper was shown to enhance the sensitivity of the sensor. Tapering can be done by reducing the diameter of the fiber by heating the fiber at its softening temperature and stretching it to reduce its diameter. Alternatively, taper can be chemically achieved by etching cladding and core using hydrofluoric acid or acetone for silica and plastic fiber respectively [16]. The evanescent field extends beyond the core-cladding interface but attenuates exponentially. Evanescent electric field is given by [17],

$$E(x) = E_0 e^{\left(\frac{-x}{d_p}\right)} \tag{1.1}$$

Where, x is the distance from the fiber core, starting at x = 0 at the core-cladding interface, E_0 is the magnitude of the field at the interface, and d_p is the penetration depth, which is the distance where the evanescent field decreases to 1/e of its value at the core-cladding interface and is mathematically described as [18]-

$$d_p = \frac{\lambda}{2\pi\sqrt{{n_{co}}^2 \sin\theta^2 - {n_{cl}}^2}} \tag{1.2}$$

Where, λ is the wavelength of the light source, θ is the angle of incidence of the light at the core/cladding interface; n_{co} and n_{cl} are the refractive maximum value at the optimum radius of curvature, after which the sensitivity gradually decreases.

1.3 Optical Filters and Applications

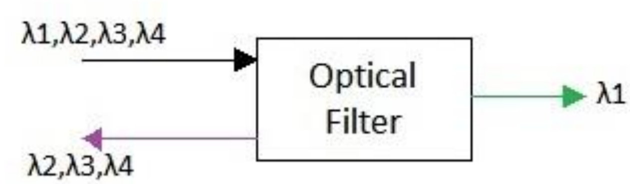

Figure 1.2 Optical filter showing transmission of λ1 and reflection of λ2, λ3, λ4 [19]

An optical filter, also called a light filter, is a device that selectively passes or blocks light of a specific wavelength or range [19]. It is used to change the spectral properties of light by passing certain wavelengths and attenuating or blocking others. Optical filters are widely used in various applications such as photography, spectroscopy, microscopy, telecommunications, display technology and scientific research [20]. Optical filters can be designed to transmit specific colors and wavelength ranges such as red, green, or blue filter used in color photography. They can also be designed to block specific wavelengths such as Ultraviolet (UV) or infrared (IR) filters used to protect the eyes and sensors from harmful radiation. In short, an optical filter is a device that selectively transmits, reflects, or attenuates light of a specific wavelength or range of wavelengths [21].

1.3.1 Optical Filter Terminology

Although filters share many of the same specifications with other optical components, there are several unique filter specifications that must be understood in order to understand and effectively determine which filter is best for your application.

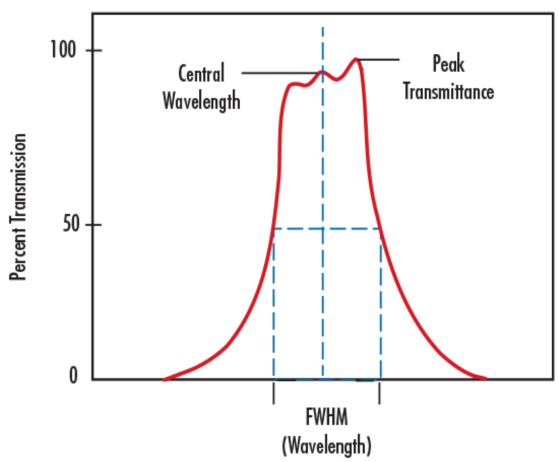

Figure 1.3 Plot between percent Transmission vs wavelength [20]

1. **Central Wavelength**

   The center wavelength (CWL), used to define bandpass filters, describes the midpoint of the spectral bandwidth that the filter passes. Traditional photo-coated filters tend to achieve maximum transmittance near the central wavelength, while hard-coated photo filters tend to have fairly flat transmission profiles across the spectral range [19].

2. **Bandwidth**

   Bandwidth is a range of wavelengths that refers to a specific part of the spectrum that transmits incident energy through a filter. Bandwidth is also known as HPBW (Figure 1.3).

3. **Half Power Bandwidth (HPBW)**

   Half Power Bandwidth (HPBW) describes the spectral bandwidth that a bandpass filter will pass. The upper and lower limits of this bandwidth are determined at the wavelengths at which the filter reaches 50% of the maximum transmittance. For example, if the filter's maximum transmittance is 90%, the wavelengths at which the filter achieves 45% transmittance will determine the upper and lower limits of the HPBW. HPBWs of 10 nm or less are considered narrow bands and are commonly used for laser cleaning and chemical detection. HPBW 25-50 nm is commonly used in machine vision applications; HPBW greater than 50 nm is considered broadband and is commonly used in fluorescence microscopy applications [22].

4. **Optical Density**

   Optical density (OD) describes the amount of energy that is blocked or removed by a filter. High optical density value indicates low transmittance and low optical density value indicates high transmittance. Optical densities of or more are used for extremely high blocking needs such as Raman spectroscopy or fluorescence microscopy. An OD of 0.8 to 0.9 is ideal for laser separation and cleaning, machine vision, and chemical detection, while an OD of 0.2 or less is ideal for classification and spectroscopy commands. color separation [20].

1.3.2 Applications

Optical filters are used in a wide range of applications in various fields. Here are some common uses for optical filters.

1. **Photography and Cinematography:**

   Optical filters, such as color filters and neutral density filters, are widely used in photography and cinematography to manipulate color balance, enhance contrast, control exposure, and create artistic effects [21].

2. **Spectroscopy:**

   Optical filters are essential in spectroscopy to select a specific wavelength range for analysis. They are used to isolate and transmit specific spectral lines or bands of interest, enabling accurate measurement and analysis of materials based on their unique spectral signatures.

3. **Microscopy:**

   Optical filters play an important role in microscopy by enhancing contrast, reducing background noise, and enhancing specific features of a sample. For example, fluorescence microscopy relies heavily on filters that select excitation and emission wavelengths, allowing visualization of fluorescently labeled samples.

4. **Telecommunications:**

   In telecommunications, optical filters are used for signal processing, multiplexing and demultiplexing of optical signals. Wavelength division multiplexing (WDM) systems use filters to separate and combine different optical channels of different wavelengths, enabling high-capacity data transmission over optical fibers [23].

5. **Laser system:**

   Optical filters are used in laser systems for beam shaping, wavelength selection, and filtering of unwanted laser radiation. They help control the laser output characteristics and ensure the desired wavelength or spectral purity.

These are just a few examples of the various uses of optical filters. Your specific application and requirements will determine which filter type to use such as Color filters, interference filters, polarizers, or special filters designed for specific purposes.

1.4 Plasmonic Structures

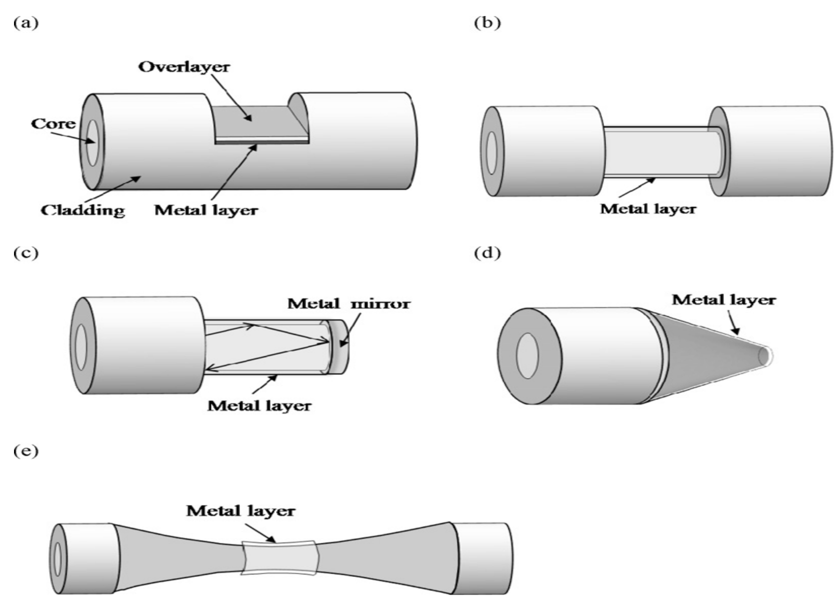

Figure 1.4 General SPR fiber-optic sensor schematics with (a) D-shape fiber, (b) cladding-off fiber, (c) end-reflection mirror, (d) angled fiber tip, and (e) tapered fiber [4]

Plasmonic structures are engineered nanostructures used to manipulate and control the interaction of light with nanoscale metallic materials. These structures make use of plasmonics phenomena involving collective oscillations of free electrons in metals in response to incident electromagnetic radiation. Plasmonic structures are typically composed of noble metals such as gold, silver, and aluminum, and exhibit strong plasmonic properties in the visible to near-infrared region of the electromagnetic spectrum [24]. By precisely engineering the shape, size and arrangement of these metallic nanostructures, it is possible to control and manipulate the behavior of plasmons, enabling diverse applications in nanophotonics, sensing, imaging and energy conversion.

1.4.1 SPP and SPR

Surface Plasmon Polariton (SPP)

The study of plasmonics involves the generation, control, and detection of plasmons as information carriers. Plasmon is a collection of electric charge carriers with quanta energy of $\hbar\omega_p$, where ω_p is the plasma frequency and it gives the effect of applying external electric field on the plasmon characteristics given by equation (1.3) [25]; $\hbar$ is the Planck's constant.

$$\omega_p = \sqrt{\left(\frac{e^2\, n_e}{\epsilon_0 m_e}\right)} \tag{1.3}$$

Where e is the electrons electric charge, m_e is the effective mass and n_e is electrons density. The carrier density of metals is usually 10^{22} cm^{-3} and for highly doped semiconductors is 10^{19} cm^{-3}. These high-density electrons behave like oscillating plasmons in plasma frequency ω_p, normally for metals, its value is 10^{15} Hz.

of plasmons and photons at the metal-dielectric boundary leading to surface polarized plasmon (SPP) as shown in Figure 1.5. It describes a metal-dielectric boundary where the midpoint of z > 0 is lossless dielectric has dielectric constant ϵd and medium for z < 0 is metal with dielectric constant ϵm [26]. SP mode is always horizontal magnetic TM in nature. SPP surface plasmon polarization can bind light into a several nanometers on the surface of the metal interface [25]. this can used to reduce the size of photonic devices to a large extent. Therefore, SPP combines the advantages of electronics and photonics for fabrication of nanophotonic devices.

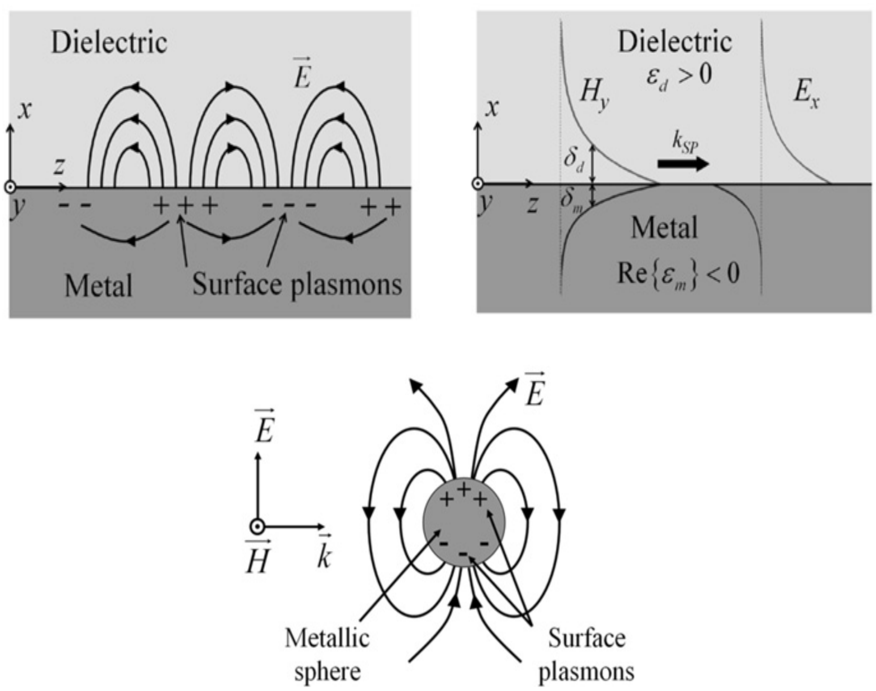

Figure 1.5(a) Surface plasmon polariton (SPP) propagating along the interface between the dielectric (b) Field distribution of the SPP (c)Schematic diagram of the localized surface plasmon resonance in a metallic sphere [27]

The Expression [27] for dispersion relation of the SP mode for the dielectric-metal boundary shown in figure 1.10b is as given below.

$$\beta = k_0\sqrt{\left(\frac{\epsilon_1\epsilon_2}{\epsilon_1+\epsilon_2}\right)} \qquad (1.4)$$

Where β is the propagation constant in the x direction and $k_0 = 2\pi/\lambda$ is the free space wave number; wavelength in free space is denoted by λ_0. The permittivity of a lossless metal in the optical region [25] is given by the Drude model as:

$$\epsilon_2 = 1 - \frac{{\omega_p}^2}{\omega^2} \tag{1.5}$$

Here ω is the angular frequency of light and ω_p is the plasma frequency of metal. Substituting the expression of equation (1.5) for ϵ_2 in equation (1.4), we obtain the dispersion relation of SP for a lossless dielectric-metal boundary.

$$\beta = k_0 \sqrt{\left(\frac{\epsilon_1 \left(1 - \frac{{\omega_p}^2}{\omega^2}\right)}{\epsilon_1 + 1 - \frac{{\omega_p}^2}{\omega^2}}\right)} \tag{1.6}$$

β is very close to $k_0\sqrt{\epsilon_1}$ for smaller values of ω. In this case the SP wave penetrates the dielectric to a great depth. As ω moves closer to the surface plasmon frequency (ω_{SP}), β gets closer to infinity. This phenomenon is known as surface plasmon resonance [27]. The wave slows dramatically at the surface plasmon resonance frequency, and the field on either side of the interface becomes extremely small i.e., for short wavelengths the SP mode is confined closer to the surface and the distance of propagation is small and as the wavelength is increased, the SP is less confined and hence the propagation distance is increased.

Surface Plasmon Resonance (SPR)

The SPR technique is well known for its very sensitive measurements of chemical and biological parameters. The Kretschmann configuration is one of the common configurations for the SPR, which consists of a metal layer placed directly on the base of the prism. Recently, metallic fiber optic SPR configurations are attracting more attention [28] because the integration of SPR technique with fiber technology has brought about many advances in fiber-optic sensing technology. The fiber optic SPR system has several advantages such as small, simple, flexible and allows remote sensing compared to the prism SPR system.

A typical SPR sensor system consists of a thin metal layer coated on a dielectric plate through which light is transmitted. The charge density oscillations occurring at the metal-dielectric interface are known as surface plasma oscillations. These collective oscillations or surface plasmons undergo resonance when excited with the corresponding wavelength. The quantity of these plasma oscillations are called surface plasmons. As shown in Figures 1.11a and 1.11b, a longitudinal electric field generated by the surface plasma oscillations at the metal-dielectric interface decays exponentially in both media.

By solving Maxwell's equations, surface plasmon wave propagation constant is given by [29]:

$$K_{sp} = \frac{\omega}{c} \sqrt{\left(\frac{\varepsilon_m \varepsilon_\delta}{\varepsilon_m + \varepsilon_\delta}\right)} \qquad (1.7)$$

Where K_{SP} is continuous across the metal-dielectric interface, ω is the frequency of incident light, c is the speed of light, sm is the dielectric constant of the metal, and s_m is the dielectric constant of the metal. dielectric environment. The transmission constant of direct light in the dielectric medium is less than that of the surface plasmon wave at the metal-dielectric interface, for this reason direct light cannot excite the surface plasmon. Therefore, the excitation of the surface plasmon is performed by a transform wave at the dielectric-metal interface. The propagation constant of the transform wave at the dielectric-air interface is given by [29]:

$$K_{ev} = \frac{\omega}{c}\sqrt{(\varepsilon_p)}\sin\theta \tag{1.8}$$

When the incident angle θ is equal to or greater than the critical angle, total internal reflection takes place at the dielectric-metal interface producing a damping wave. Surface plasmon resonance occurs when the wave vector of the ephemeral wave exactly matches with the same frequency as the surface plasmon. The surface plasmon resonance condition is given by the equation [29]:

$$\frac{\omega}{c}\sqrt{(\varepsilon_p)}\sin\theta = \frac{\omega}{c}\sqrt{\left(\frac{\varepsilon_m\varepsilon_\delta}{\varepsilon_m+\varepsilon_\delta}\right)} \tag{1.9}$$

When the resonance condition (Equation 1.9) is satisfied, surface plasmon resonance occurs at the metal-dielectric interface, resulting in energy transfer from incident photons to surface plasmons. Resonance thus reduces the emitted light energy. In a typical prism based SPR The system output is the normalized reflected intensity (R) measured as a function of angle of incidence, keeping frequency, metal, and dielectric layers constant. At resonance, we observe a sharp drop in the intensity of the reflected light with the resonance angle (Fig 1.11c). Unlike his prism based SPR sensors, which use angular interrogation methods, fiber optic SPR sensors generally use spectral interrogation methods because they initiate all guided modes within the fiber. Detection is done by observing wavelengths corresponding to spectral dips [30].

1.4.2 Plasmonic Waveguides

A surface plasmon is a gas of free electrons that exists on the surface of a metal. When electromagnetic waves and surface plasmons are coupled, they are excited and begin to oscillate synchronously with the electromagnetic waves, forming surface waves called surface plasmon polaritons (SPPs) [31]. SPPs exist only at metal-dielectric interfaces. SPP has many unique properties that are very important for practical applications. Unlike dielectric waveguides, where optical confinement is limited by diffraction, plasmonic waveguides can “squeeze” light down to sub-wavelength scales [32]. This offers the possibility of scaling down photonic devices to the size of transistors which may result in successful integration of photonics and electronics. Though the field of plasmonics has several advantages it suffers from large ohmic losses. Metals have complex permittivity in optical region hence SPPs have a large propagation loss. This is a major limitation that has prevented plasmonics from becoming a more useful technology. Surface plasmons have a direct relation between material property and incident light which makes it easy to control and manipulate.

These properties make plasmonic waveguides better candidates for on-chip nanophotonic devices in light modulation, switching, sensing, and photodetection applications [31]. Several plasmonic waveguide structures such as MIM metal-insulator-metal, MIS metal-insulator-semiconductor, V-Grove MIM, and IMI have been proposed to overcome the ohmic losses, as shown in Fig. 1.12 only some of them are shown.

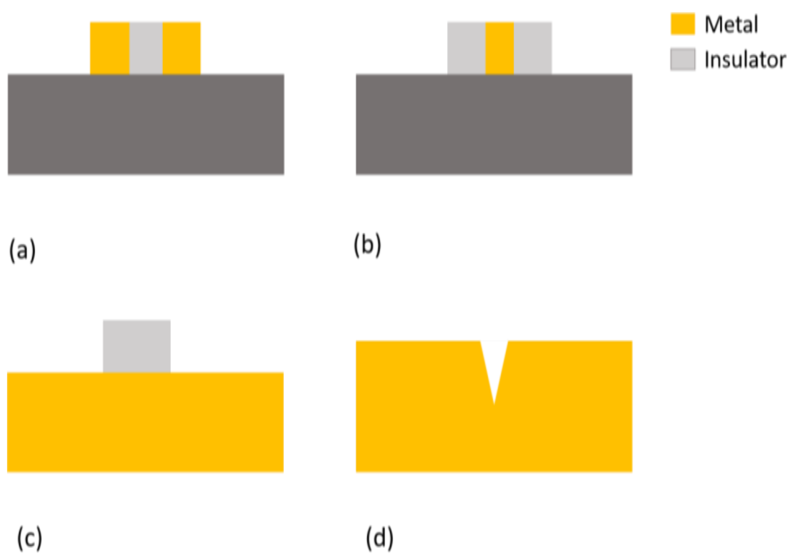

Figure 1.6 Various types of plasmonic waveguide (a) MIM (b) IMI (c) dielectric-loaded plasmonic waveguide (d) V grove MIM [32]

1.4.2.1 Losses in Plasmonic Waveguides

Plasmonic waveguides undergo various metallic losses Emission and phase shift due to collisions between electrons and generate hot electrons. These hot electrons radiate energy All energy is lost in the form of heat, so losses are high short propagation length in the plasmonic waveguide [32]. This Energy dissipation in the SPP causes local heating on-chip device. There are several ways to deal with this issue Recommended.

a) **Use of gain media:** An optical gain medium can be used for this. Reduces or eliminates SP propagation loss. Because SP suffers There is considerable propagation loss, but the gain medium transmits well. Amplification [9] to achieve significant diffusion. Nevertheless, Gain assist SP has great potential for on-chip integration Gain media with plasmonic waveguides are not always simple. And this approach may not be the best solution for many Application [13].

b) **Improved Plasmonic Waveguide Design:** All Plasmonic Guides A balance must be struck between loss and imprisonment. increase of Restrictions are always accompanied by spread increases loss. However, the degree of this trade-off is not the same for everyone. A type of plasmonic guide [7]. many different kinds Plasmonic guides are designed for good balance Between captivity and loss.

1.4.3 Nanophotonic Focusing

Nanophotonic focusing refers to the process of concentrating or focusing light waves at the nanoscale. It involves manipulating and controlling the propagation of light using nanoscale structures or devices [33]. Nanophotonic focusing enables the precise control and manipulation of light at dimensions smaller than the wavelength of light, allowing for enhanced spatial resolution and the creation of compact and efficient optical systems. There are several approaches to achieving nanophotonic focusing, including the use of plasmonic structures, metamaterials, and photonic crystals. These structures are designed to interact with light waves and manipulate their propagation, leading to desired focusing effect [34].

Plasmonic structures rely on the interaction between light and surface plasmons, which are collective oscillations of electrons at the surface of a metal. These structures are typically designed with nanoscale features, such as metallic nanoparticles, nanowires, or nanoscale apertures [35]. By precisely engineering the shape, size, and arrangement of these structures, it is possible to manipulate and confine light at the subwavelength scale, achieving nanophotonic focusing. Metamaterials, on the other hand, are artificially engineered materials that exhibit extraordinary optical properties not found in natural materials. They are composed of subwavelength building blocks arranged in specific patterns to achieve desired electromagnetic responses. Metamaterials can be designed to possess negative refractive index, which allows for unique control over light propagation [33]. By tailoring the parameters of metamaterial structures, such as their geometry, composition, and electromagnetic properties, nanophotonic focusing can be realized.

Photonic crystals are periodic structures that possess a bandgap, which is a range of wavelengths in which light propagation is forbidden. These structures are engineered to control and manipulate the flow of light based on the principles of constructive and destructive interference. By tailoring the lattice structure and refractive index contrast within the photonic crystal, light can be effectively guided and focused at the nanoscale [36].

Nanophotonic focusing has a wide range of applications across various fields. In microscopy, it enables sub diffraction-limited imaging and the visualization of nanoscale details. In nanolithography, it allows for the precise fabrication of nanoscale patterns and structures [37]. In optical data storage, it enables high-density and high-capacity data storage on small optical discs. In integrated photonics, it plays a crucial role in the miniaturization and efficiency enhancement of photonic devices.

Overall, nanophotonic focusing offers unprecedented control and manipulation of light at the nanoscale, leading to a multitude of applications in fields such as imaging, sensing, information technology, and nanotechnology [33].

1.5 Organization of the Thesis

The thesis is organized in five chapters starting with an introduction to nanophotonics and literature survey, one chapter consisting of the original research work followed by the conclusion and the future scope.

Chapter 2 Literature Survey: In this chapter, a brief literature review of the fiber optic devices, plasmonics based nanophotonic applications is presented, which includes many currently reported works.

Chapter 3 Fiber based filtering and mode transformation: In this chapter, tapered fiber optic device is analyzed for the filtering and mode conversion process.

Chapter 5 Conclusion and Future Scope: This chapter outlines the thesis and briefly discusses the future scope of the project.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

In recent years, researchers have focused on developing novel optical fiber devices and plasmonic related structures, aiming to enhance performance, miniaturize devices, and unlock new functionalities. This chapter provides an overview of recent literature on fiber optic filters, plasmonic structures, and their applications in high density integration circuits or devices.

2.2 Review on Fiber Optic Filters

Advancements in fiber optic filters research have led to the development of sophisticated filter architectures, such as fiber Bragg gratings, Fabry-Perot interferometers, and thin-film filters, empowering precise control over transmitted and reflected light in fiber optic systems. Here are some reviews on fiber optic filters:

Benvenuti L et.al-20011 [38] This paper presents a new design methodology for fiber-optic filters that can process high-speed signals without costly electrooptic and optoelectronic conversions. The authors propose a new design methodology to realize an arbitrary filter as a difference of two positive filters, thus overcoming any performance limitation. The paper also introduces three elementary blocks for optic filter implementation and provides explicit solutions for positive realizations of third- and fourth-order transfer functions.

Frankel M et.al-2015 [39] The document describes a fiber-optic tunable microwave transversal filter with continuously tunable unit time delays. The filter has eight taps with progressively longer segments of high-dispersion fiber and can be tuned by varying the wavelength of the optical carrier. It exhibits bandpass characteristics with a Q of 30 and a passband continuously tunable over an octave from 8.9 to 18.2 GHz with a single low-voltage control signal.

K. McCallion et.al-2004 [40] The article describes the development of a tunable fiber-optic bandpass filter using evanescent interaction between a single-mode optical fiber and a high-index, multimode overlay waveguide. The resonance spacing can be controlled by varying the overlay waveguide thickness and material index, and the position of the transmission passbands can be tuned by varying the refractive index. The device has low insertion loss and high extinction ratio and has practical applications in tuning fiber lasers and suppressing noise in fiber amplifiers.

Zou X et.al-2013 [41] Researchers have developed an all-fiber optical filter with a narrow bandwidth of 650 MHz and a rectangular shape factor of 0.513. The filter operates in transmission with low loss and has a stop-band bandwidth of 30.4 GHz and a rejection ratio of 50 db. The work was supported by various organizations.

Capmany J et.al-2005 [42] The paper discusses the synthesis of fiber-optic delay line filters, including methods for positive and negative coefficient filters, implementation using optical switching matrices, and examples of lowpass, bandpass, and high pass filters. The article also provides a general procedure for the synthesis of arbitrary filters and includes information about the authors' research interests and background.

2.3 Review on Fiber based Plasmonics

Optical fiber based plasmonics has emerged as a promising research frontier, offering a synergistic platform for manipulating light on the nanoscale and bridging the gap between traditional photonics and nanotechnology. Many research papers are devoted to optical fiber based plasmonics and few of them will be discussed in this section.

Rifat A et.al-2019 [26] This article provides a comprehensive review of micro-structured optical fiber-based plasmonic sensors, which use surface plasmon resonance to detect changes in refractive index. The article covers different types of fibers, coatings, and materials used to enhance sensitivity, as well as potential applications in biosensing and chemical sensing. The article also discusses recent developments in miniaturization and integration of plasmonic sensors, including the use of smartphones for detection.

Sharma A et.al-2018 [43] This document is a collection of articles and research papers discussing advancements in fiber optic sensors based on surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR) technology. The articles cover various types of fibers, metals, and materials used in SPR sensing, as well as their applications in biosensing, gas detection, temperature sensing, and chemical sensing. The document also discusses future prospects for developing cost-effective and reusable sensors for detecting a broad range of bio-and gas samples.

Yingjie Zhang et.al-2012 [44] The document discusses the development of a new broadband single-polarization optical fiber with high extinction ratio based on surface plasmon resonance (SPR) by researchers from Harbin Engineering University in China. The modified SPR fiber shows promising application in high-quality fiber-integrated polarizers. The article also discusses various types of fiber optic sensors and polarizers, including those based on graphene, long-period gratings, and D-shaped hole fibers, and their potential applications.

Sarker H et.al-2021 [45] The document describes a proposed slotted photonic crystal fiber-based plasmonic biosensor for detecting chemical substances. The sensor is designed using a simplified version of the highly sensitive plasmonic sensor and is studied numerically using the finite element method. The proposed sensor has a simple, symmetrical, and cost-effective design and offers higher sensitivity than other PCF-based sensors. The sensitivity of the sensor is studied based on parameters such as confinement loss, wavelength sensitivity, sensor resolution, and amplitude sensitivity. The proposed sensor can detect analytes with different refractive indices, and it is simple and feasible to manufacture for various applications in biochemical industries.

Bucaro J et.al-2011 [46] This paper discusses a new type of optical fiber sensor that uses the interaction between the guided mode of a single-mode optical fiber and the surface plasmon. The sensor structure can be customized for applications where refractive indices of the sensing media are much lower than those of the optical fibers. The sensor sensitivity was evaluated and found to be between 9 x 10-6 and 3.6 x 105 index of refraction units.

2.4 Research objectives

After doing a deep literature survey on the past works related to novel fiber optic devices, optical filters. I found the following area of improvement and worked through that.

Following are the objectives of the research work:

1. To design and analyse the tapered optical fibre with or without cladding, for achieving the characteristics of a filter.
2. To achieve the minimum losses in the coupling of different optical fibres.
3. Mode Transformation from optical into plasmonic.

Chapter 3

Fiber based Optical filtering and Mode Transformation

3.1 Introduction

Optical signals in optical fibers often require manipulations such as filtering and mode conversion for the following reasons:

1) **Bandwidth management:** Filtering operations are performed to manage the available bandwidth in fiber optic systems. Optical signals may contain a wide range of frequencies [21]. Filtering allows you to select specific frequency ranges of interest while attenuating unwanted frequencies. This helps optimize the use of available bandwidth and minimize interference between different channels in wavelength division multiplexing (WDM) systems.
2) **Signal conditioning:** Optical signals can be distorted during transmission due to various factors such as dispersion, nonlinear effects, and noise. A filtering process compensates for this distortion and improves the quality of the transmitted signal. For example, dispersion compensation filters are used to reduce the effects of chromatic dispersion in long-haul fiber optic systems.
3) **Mode conversion:** Optical fibers can support different types of light propagation, such as single mode fiber and multimode fiber. Mode conversion operations are necessary when transitioning between different fiber types or connecting fiber optic devices with different modal characteristics [47]. Mode converters enable efficient optical coupling between fibers with different mode characteristics, ensuring proper signal transmission.
4) **Signal multiplexing and demultiplexing:** In optical communication systems, multiple signals are often sent

simultaneously at different wavelengths or modes over a single optical fiber. Filter operations such as multiplexers and demultiplexers are used to combine or separate these signals at the transmitter and receiver respectively. This enables high-performance data transmission and efficient utilization of the optical spectrum.

Overall, the manipulation of filters and mode conversion in fiber optic systems is critical to optimizing signal quality, managing bandwidth, supporting different fiber types, and achieving efficient multiplexing and demultiplexing of optical signals. These operations play an important role in achieving reliable, high-performance optical communications.

3.2 Proposed device design

The proposed structure is a 3-Dimensional tapered optical fiber in which one segment performs filtering and the other will perform mode transformation. The design consists of parameters- Bottom radius(R) and top radius(r). Based on the requirement these parameters are varied, in case of filter, R =1μm and r =0.5μm satisfy the objectivity of the filter. Practically optical fiber is a tube-like structure (cylinder shape) but the device design consists of tapered structure of optical fiber. Tapering can be done by heating the fiber to reduce the fiber diameter and stretching at the softening point to reduce the diameter. Alternatively, it can also be chemically tapered by etching cladding and core using hydrofluoric acid or acetone for silica and plastic fiber respectively. For conversion of photonic mode into a plasmonic mode, creation of metal semiconductor interface is required therefore a metal is wrapped around the tapered structure. Silver having the maximum conductivity will show the significant metal for the mode conversion. The thickness of the metal show no effect on the results of mode transformation. The overview of the last chapter gives an idea of proposing the design of a structure which can work as a filter and can transform the mode of the light. The design should be such that it can follow certain characteristics-

1. Selectivity should be very high.
2. Bandwidth should be as minimum as possible.
3. Transmission fraction should be close to unity.
4. Coupling loss between the waveguides should be minimal.
5. The efficiency of the device should be very high.

The proposed device design is shown in figure3.1.

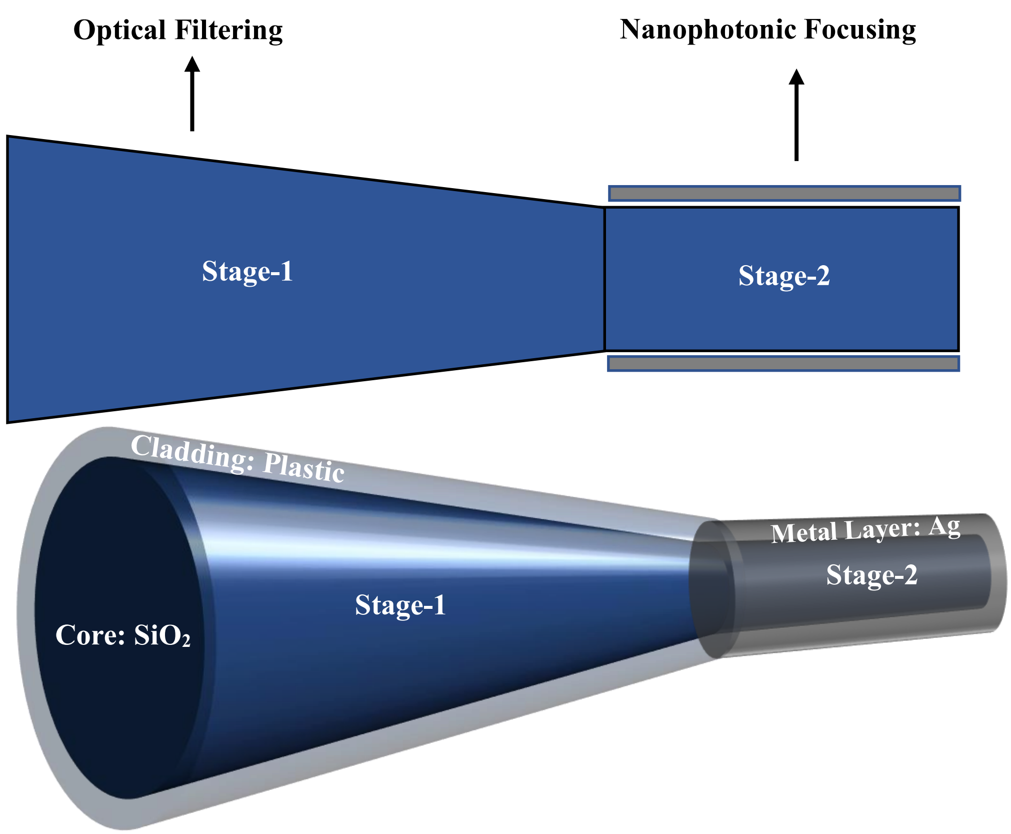

Figure 3.1 Illustrates both the cross-sectional view and 3D representation of the proposed device. The device is into two stages. In stage 1, there are two distinct components: a silicon dioxide core and a plastic cladding. 2, a layer of silver metal is added over the optical fiber.

3.3 Optical Filtering

A filter is a device that selectively modifies or extracts certain components of a signal while attenuating or removing unwanted components. It is used to manipulate the frequency/wavelength content and other characteristics of a signal. The characteristics that the filter needs to satisfy are given as-

1. Normalized Power should be unity at cut-off wavelength.
2. HPBW should be as low as possible ($0.1\ Hz$).

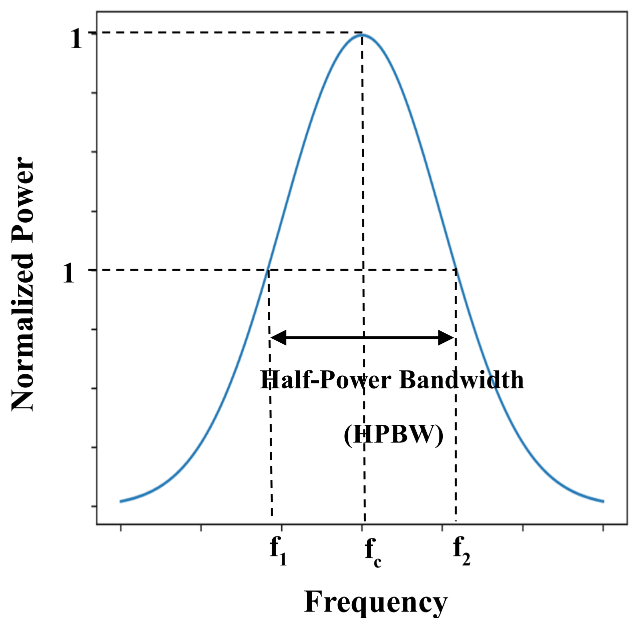

Figure 3.2 curve between normalized power vs frequency

Fig3.3 depicts the picture of tapered optical fiber which consists of four different dimensions: Top radius(r), bottom radius(R), length of the fiber(L) and wavelength of the source(λ). The source is kept at the bottom part of the fiber and the monitor (to take the output) is kept at the top part of the fiber.

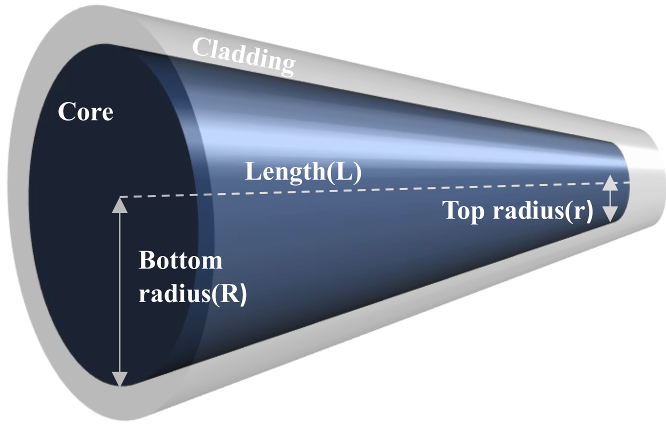

Figure 3.2 Tapered optical fiber

The device design, simulation and analysis are done with Lumerical using Finite Difference Eigenmode (FDE) and Finite Difference Time Domain (FDTD) solvers [35]. The different plots are being taken by varying the dimensions of the tapered fiber.

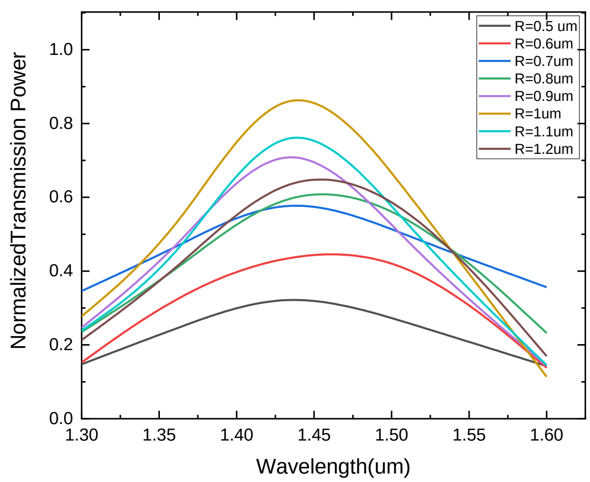

Figure 3.3 Plot between normalized Power and wavelength @ $\boldsymbol{r = 0.5\mu m, L = 5\mu m \& R, \lambda = variable}$

Figure3.4 shows the plot between normalized transmission power and wavelength by taking r=0.5µm, L=5µm and λ, R variable. As fiber shows different behavior at different dimensions. But at the R=1µm, it is giving the maximum peak Power(P)= 0.83 at λ= 1.43μm. This shows that at this dimension, the tapered optical fiber shows the characteristics of a filter. But to declare these dimensions, it needs to check its variability in relation to the other dimensions. Hence fig 3.5 is showing the variation of top radius 'r' w.r.t R=1μm and L=5μm which is plotted between normalized power vs wavelength. This plot shows the maximum peak at r = 0.5μm and λ_{cutoff} = 1.43μm, It can be concluded that at dimensions r= 0.5μm, R=1 μm, this device can behave as filter for λ = 1.43 μm. Furthermore, it is not the right time to say before examining the other plots with other combination of parameters.

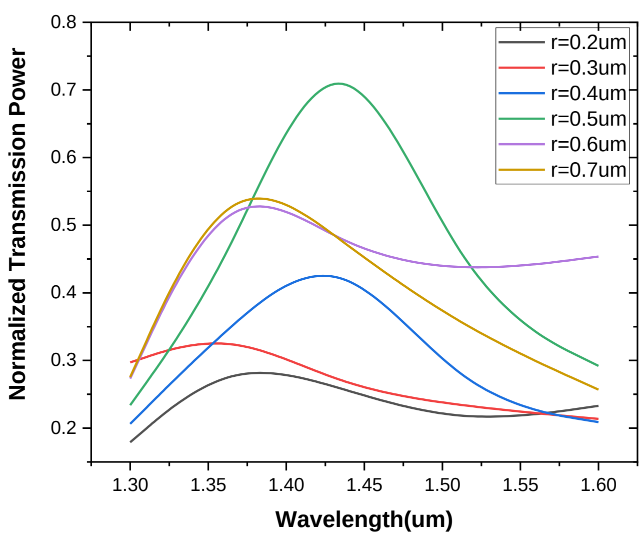

Figure 3.4 Plot of Normalized Transmitted Power vs wavelength @ $R = 1\mu m, L = 5\mu m$ & $r, \lambda = variable$

Similarly, fig 3.6 depicts that the combination of R, r and L is 1 μm, 0.5 μm, 5 μm satisfies the characteristics of a filter. Moreover, it can concluded from the plot is that as the length of the fiber decreases the transmission power also decreases but up to a certain length i.e. at L=2.5 μm passing the wavelengths of low power than at L = 5 μm.

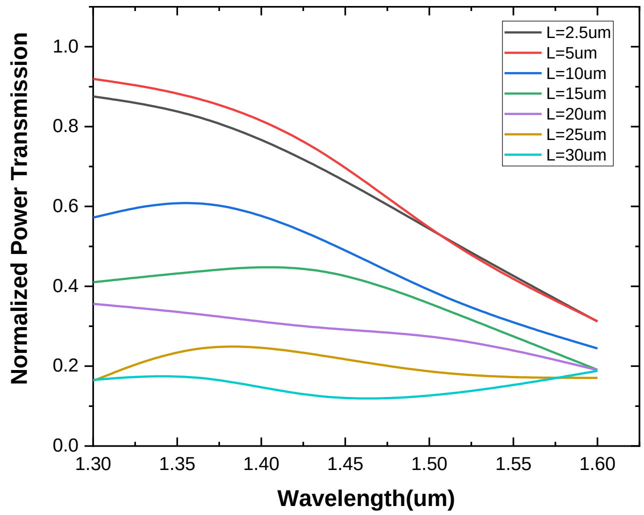

Figure 3.5 Plot of Normalized Power vs Wavelength @ $\boldsymbol{R = 1\mu m, r = 0.5\mu m}$ & $\boldsymbol{L, \lambda = variable}$

After analyzing all the plots w.r.t wavelength, the characteristics of the tapered fiber with a dimension of R, r, L shows that the filtering of the wavelength at 1.44 µm takes place at R=1 µm, r=0.5 µm, L=5 µm, but to optimize the results there is a need to check its authenticity by fixing the wavelength and varying the other dimensions.

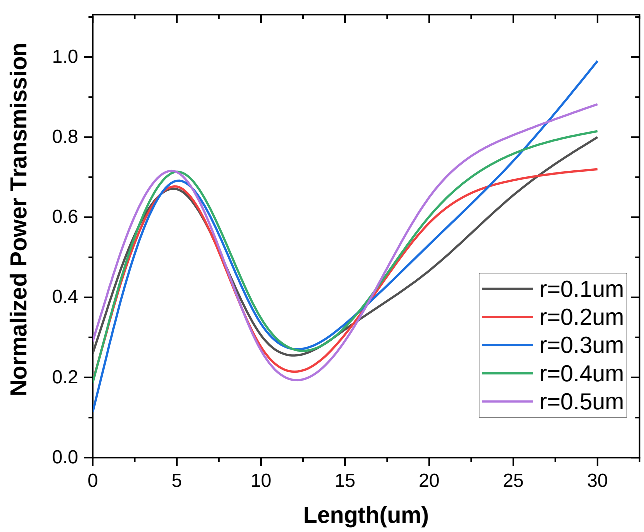

Figure 3.6 Plot of Normalized Transmitted Power vs Length @ $\boldsymbol{R = 1\ \mu m, \lambda = 1.43\ \mu m}$ & $\boldsymbol{r, L = variable}$

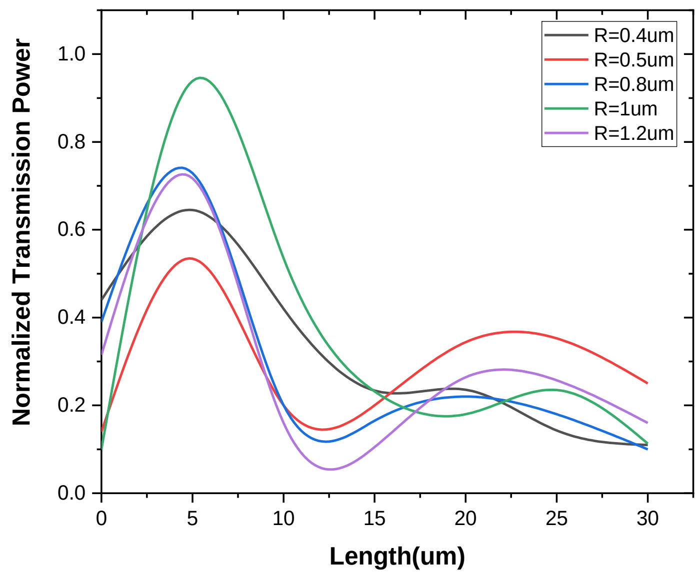

Figure 3.7 Plot of Normalized Transmitted Power vs Length @ $\lambda = \mathbf{1.43}\mu\boldsymbol{m}, \boldsymbol{r} = \mathbf{0.5}\mu\boldsymbol{m}$ & $\boldsymbol{R}, \boldsymbol{L} = \boldsymbol{variable}$

Fig 3.6 and Fig 3.7 depicts the plot between the normalized power vs Length of the fiber with r and R as variable and keeping the wavelength of the source fix at λ= 1.44 µm, both the graphs show the maximum peaks at L= 5 µm at r=0.5 µm and R = 1 µm respectively. Fig 3.8 depicts the plot between the normalized power vs Bottom radius(R) with r as variable and wavelength at 1.43 µm. As you can see the peaks of different 'r' are exactly at half of 'R' respectively that generalized the relationship between the r and R for the device design as-

$$\boldsymbol{r} = \boldsymbol{R}/\mathbf{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

It shows the design of the tapered optical filter should be such that it follows the equation (3.1) and this equation is valid only for filtering 1.44µm wavelength.

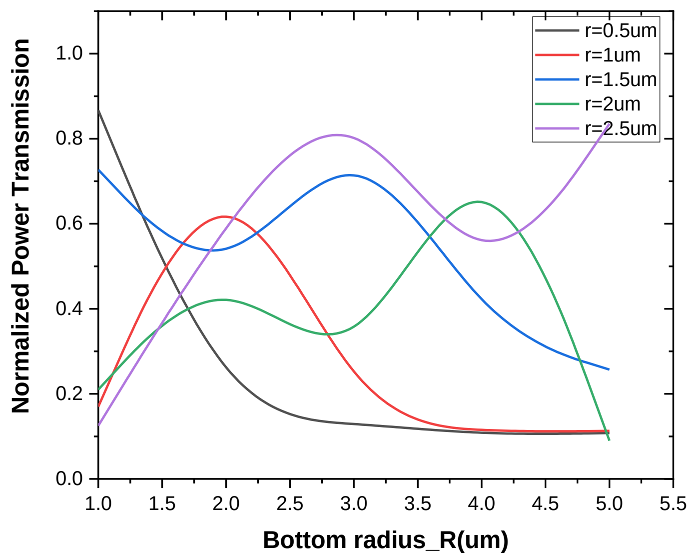

Figure 3.8 Plot of Normalized Transmitted Power vs Bottom radius(R) @ $\lambda = 1.43\mu m, L = 5\mu m$ & $R, r = variable$

Based on the analysis conducted, Figure 3.9 presents the conclusion, which states that the tapered optical fiber, featuring dimensions of $R = 1\ \mu m, r = 0.5\ \mu m, and\ L = 5\ \mu m$, functions effectively as a filter with the following characteristics:

- Normalized Power (P) $= 0.83$
- Central wavelength (λ_c) $= 1.44\ \mu m$
- Half Power Beam Width (HPBW) $= 0.17\ \mu m$.

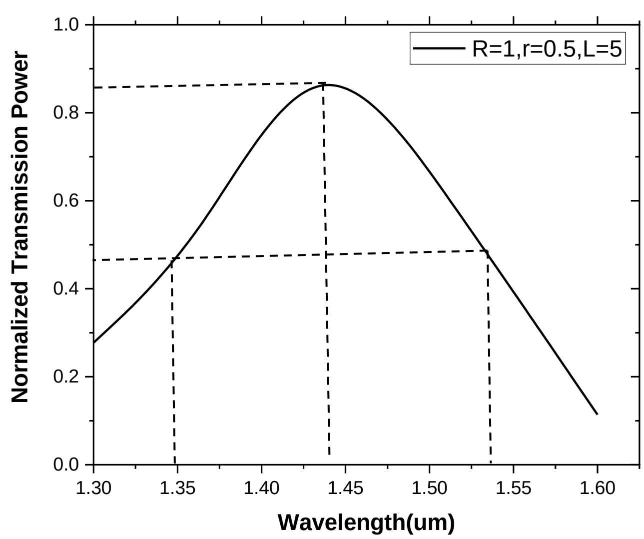

Figure 3.9Curve shows the characteristics of a filter.

3.4 Nanophotonic focusing

Nanophotonic focusing is the manipulation and control of light at the nanoscale to generate highly localized and intense optical fields. Nanostructures and materials are used to focus light into extremely small volumes while exceeding the diffraction limit of conventional optics [34].

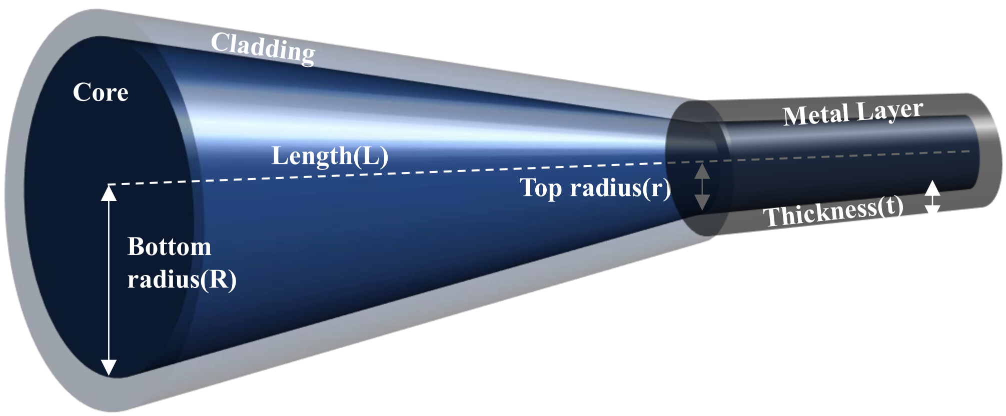

Figure 3.10 showcases a tapered optical fiber enveloped by a metal layer, characterized by a thickness denoted as 't'.

This is the second stage of the proposed device which is implemented by inserting the metal layer over the optical fiber. The diffraction limit limits the ability to focus light to a spot size greater than half the wavelength of the incident light, as described by the Abbe diffraction limit. However, nanophotonic focusing technique take advantage of the unique properties of nanoscale structures to push this limit [35].

The device design, simulation and analysis are done with Lumerical using Finite Difference Eigenmode (FDE) and Finite Difference Time Domain (FDTD) solvers [12]. Fig 3.10 shows the picture of a tapered optical fiber with plasmonic layer. In the context of a tapered optical fiber with a plasmonic layer, the aim is to enhance the interaction between light and the plasmonic material. By tapering the fiber and incorporating a plasmonic layer, the device can facilitate the conversion of optical signals from the photonic mode to the plasmonic mode. In photonic mode, the light signals are confined within the core of the optical fiber and propagate as guided electromagnetic waves. However, when the light encounters the plasmonic layer, the surface plasmons can be excited, leading to the conversion of the optical signals into the plasmonic mode. In plasmonic mode, the light is coupled to the surface plasmons and can propagate along the surface of the plasmonic layer.

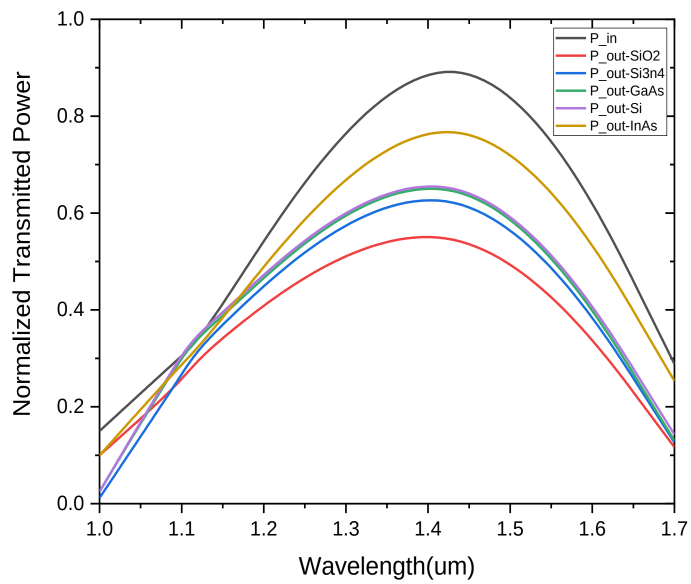

Figure 3.11 plot of normalized vs wavelength showing the coupling of two fibers.

Before the light interaction with metal, the light should be coupled from one fiber to another fiber. The coupling efficiency should be as maximum as possible. Fig3.11 depicts the coupling with different materials in which indium arsenide shows the maximum coupling w.r.t silicon dioxide. The equation:

$$\text{Coupling Efficiency}(\eta) = \frac{P_{out}}{P_{in}} \qquad (1.7)$$

Equation (1.7) shows the coupling efficiency between the fibers of different characteristics in which the maximum efficiency that we get η=81.2%. This shows 81.2% of the input power is coupled for the next stage. This extension of device makes the optical signals to convert its photonic mode into plasmonic mode. Fig 3.11 depicts the percentage of light interaction with the metal. In this case silver has the maximum conductivity showing the maximum transmission fraction among other metals.

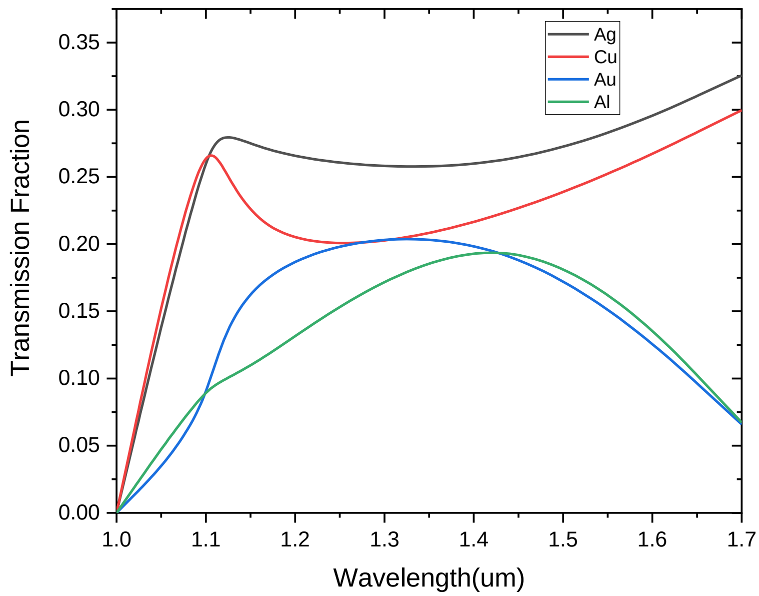

Figure 3.12 Plot between transmission fraction vs wavelength

In the mode conversion stage, a metal layer of different thicknesses is introduced to observe its impact on the transmission of light into the metal. According to the results shown in Figure 3.13 indicate that the thickness of the metal layer does not have any noticeable impact on the transmission of light, as all the plots (a), (b), (c), and (d) demonstrate the same results without any deflection.

In general, when a metal layer is introduced in an optical system, it can affect the behavior of light due to its plasmonic properties. Plasmons are collective oscillations of free electrons in a metal, and they can interact with light to confine and manipulate the electromagnetic field at the nanoscale.

The behavior of light in the presence of a metal layer depends on various factors, including the thickness of the metal layer, the material properties of the metal, and the wavelength of the incident light. In some cases, when the metal layer is extremely thin (on the order of a few nanometers), it may not exhibit significant plasmonic effects, and therefore, the transmission of light through the metal layer may remain largely unaffected.

Therefore, it is observed that the thickness does not have any impact on transmission of light into metal. The results are shown in figure 3.13, (a) shows thickness of 30nm, (b) shows thickness of 50nm, (c) shows thickness of 70nm and (d) shows 100nm thickness. In all plots the results are same without having any deflection.

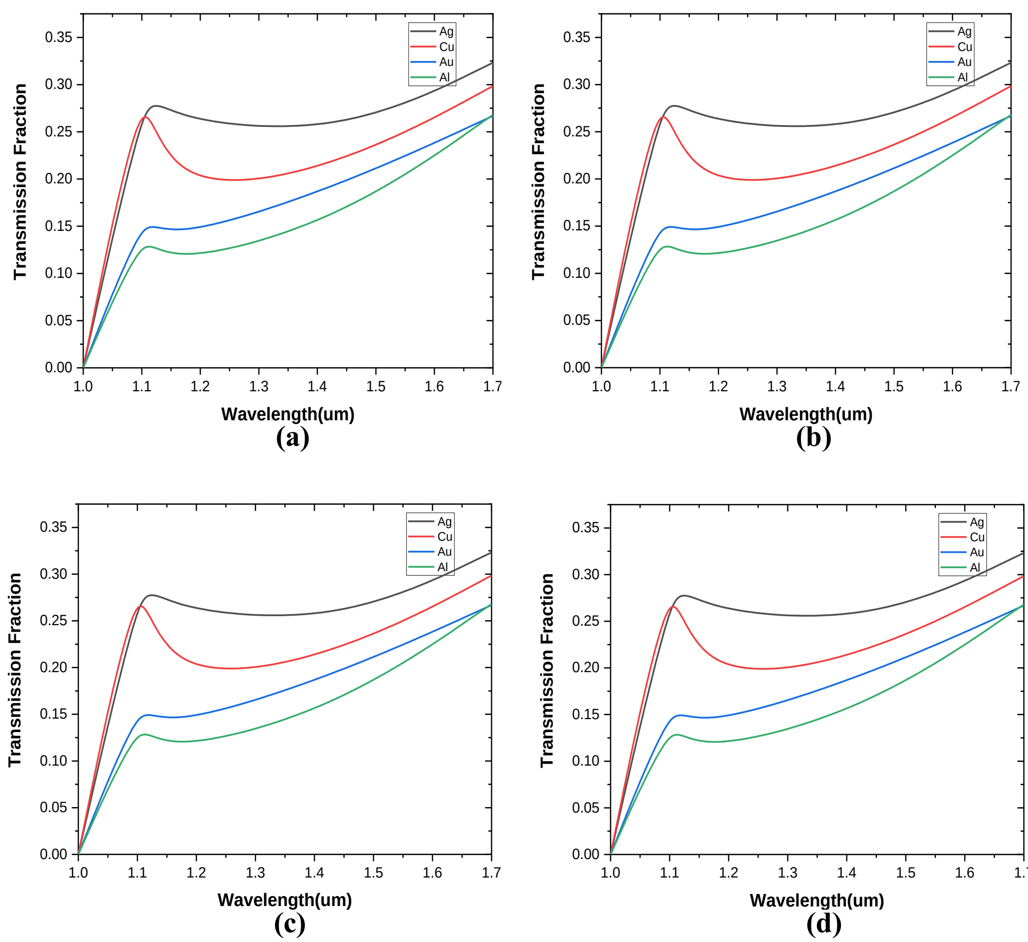

Figure 3.13 Plot between transmission fraction at different thickness(t) of the metal (a) 't'=30nm (b) 't'=50nm (c)'t'=70nm (d)'t'=100nm

Figure3.4(a) shows the plot of $|E|^2$ vs Wavelength, which depicts that the power transmitting at the interface of metal is maximum in case of silver metal. The parameter used here for demonstration of light metal interaction is shown in equation (2.0)[43] :

$$|E|^2 = \left|\frac{E_i - E_r}{E_i}\right|^2 \qquad (1.8)$$

Where E is the transmitted electric field at the metal dielectric interface, E_i is the incident Electric field and E_r is the reflected electric field.

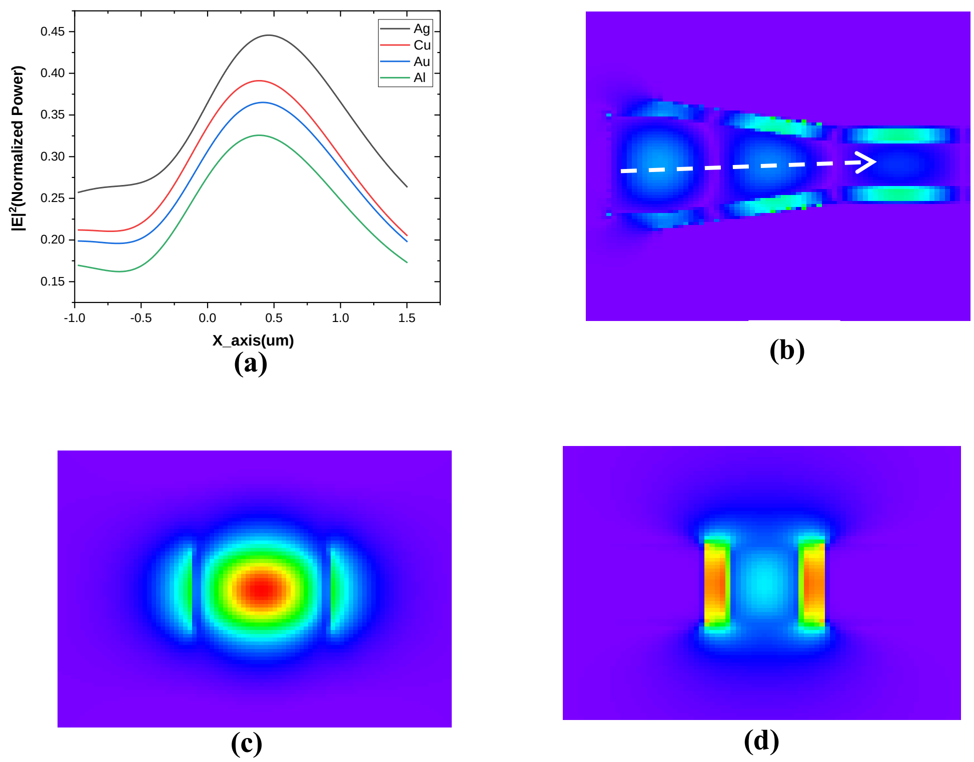

Figure 3.14 (a) Plot between |E|^2 vs X_axis (b) Top view of light propagation (c) Side view (d) Front view of the Fig3.10 shows the linkage of light with the metal as the light propagates in the tapered fiber.

The schematics of the proposed SPPs mode transformer are shown in Figure 3.14. Our proposed structure consists of two parts, one with tapered part other metal slot structure with a modulated refractive index profile in the slot region. A thin SiO2 gap region (refractive index SiO2= 1.46) separates the metal (Ag) from the high refractive index regions (Si= 3.5). Optical transmission is simulated using a three-dimensional finite-difference time-domain (FDTD) approach. From this figure, we can see that in the limit of large low-index gap width, the structure of the proposed transformer is reduced to a regular waveguide-cone pair. At this limit, the optical transmission approaches the value obtained with a normal waveguide pair taper. This is approximately 39% and 56% for two-pair tapers with $w_t = 150$ and $w_t = 200$ nm and is limited by the following limits: Radiation loss. On the other hand, reducing the gap width of the refractive-index-modulated metal slit significantly improves the transmission optical performance for TE-polarized light due to resonant coupling with the surface plasmon mode. The figure shows that the power transfer value of the modulation index transformer can be increased up to 91% and 96% respectively at $w_t = 150$nm.

Figure 3.14 Calculated optical power transfer and low index gap widths for TE and TM polarizations of the SPP mode transformer, wavelength dependence of the SPP mode transformer $W_t = 200$ nm Investigating the wavelength dependence of the proposed transformer, the calculated spectrum of the optical transmission transformer is shown in Fig3.14. This data suggests that the enhanced power transfer by SPP is indeed a broadband phenomenon, and that reversible mode conversion can be achieved within submicron length scales with insertion loss as low as 0.08 db. In summary, we have proposed a broadband plasmon mode converter that can achieve sub-wavelength mode conversion between silicon waveguides and surface plasmon modes in metal-dielectric slot structures.

3.5 Summary

The proposed design involves the utilization of a tapered optical fiber to perform two important operations: filtering and mode transformation. With a specific focus on filtering, the device effectively filters a specific wavelength, $\lambda = 1.44\ \mu m$, while achieving a normalized power of 0.83. The dimensions of the proposed design are set as follows: the larger end radius (R) is $1\ \mu m$, the smaller end radius (r) is $0.5\ \mu m$, and the taper length (L) is $5\ \mu m$.

To enable efficient mode transformation, a layer of silver metal with a thickness of $100nm$ is incorporated into the design. This metal layer plays a critical role in facilitating optimal nanophotonic focusing. Notably, the proposed device achieves an impressive coupling efficiency of 81.2%. This means that 81.2% of the input power in the form of light is successfully converted into plasmonic output power.

The design, simulation, and analysis of this device were performed using Lumerical software, a reliable tool for investigating and optimizing nanophotonic structures. Through this comprehensive approach, the device's performance and characteristics were thoroughly evaluated, enabling a better understanding of its potential applications and capabilities.

Chapter 4

Conclusion And Future Scope

Tapered Optical Filtering- The first stage involves a tapered optical fiber with Silicon dioxide as core and plastic as cladding. The specifications of tapered fiber provided are as follows:

- Bottom Radius (R): 1 μm
- Top Radius (r): 0.5 μm
- Fiber Length (L): 5 μm
- Maximum Normalized Power: 0.83 at a wavelength of 1.44 μm
- Half Power Beam Width (HPBW): 0.2 μm

This tapered fiber configuration suggests that the fiber undergoes a gradual reduction in its core radius over a length of 5 μm, resulting in a smaller tapered end radius. Tapered fibers are often used for mode conversion and efficient light coupling between different components. The maximum normalized power of 0.83 at a wavelength of 1.44 μm indicates the power level achieved within the tapered fiber. Normalized power refers to the power of the light signal normalized to the maximum power attainable in the fiber. The Half Power Beam Width (HPBW) of 0.2 μm represents the angular width of the beam where the power is half of its maximum value. This parameter describes the focusing capability of the tapered fiber.

Nanophotonic focusing- The second stage involves the maximum coupling ratio $(Pout\ /\ Pin)\ =\ 81.2\%$ between output power (Pout) and input power (Pin). The provided value of 81.2% indicates that the input power in the form of light is coupled to the metal fiber interface for mode conversion. Maximum Transmitted Normalized Power @Ag = 45% with the specification of the maximum transmitted normalized power at Ag

(Silver) material. The value provided is 45%. This indicates that when using Silver as the material, the maximum normalized power that can be transmitted through it is 45%. It implies that Silver has certain limitations in terms of its transmission efficiency or properties for the given application.

Overall, the specifications for each stage describe the performance and characteristics of the components or materials involved in the optical filtering process. These specifications provide insights into the power, coupling efficiency, and transmission capabilities within the given system or setup.

There are several future possibilities to further accomplish and extend the objective of the thesis. Following are the future scope for the presented work:

1. Apart from Filtration and Mode Conversion: While filtration and mode conversion are important operations in optical systems, there are several other operations that can be performed using optical fibers and nanophotonic components. Some potential areas of exploration include- Signal modulation, Optical sensing, nonlinear optics, quantum optics.

2. In nanophotonic focusing, the propagation length of electromagnetic (EM) waves is limited. Ohmic losses occur due to the conversion of electrical energy into heat as a result of resistance in the material. To mitigate the effects of ohmic losses, it is essential to use materials with lower electrical resistivity or explore alternative materials with lower losses in the desired spectral range. For instance, optimizing the choice of metals or dielectric materials used in the system can help reduce ohmic losses and improve the propagation length of EM waves.

3. Improving Nanophotonic Focusing Efficiency: Nanophotonic focusing efficiency can be enhanced through various means. Some potential avenues for improvement include- Advanced nanofabrication techniques, Novel materials, Hybrid structures, Active control.

By advancing these aspects, researchers and engineers can work towards achieving higher precision, improved efficiency, and better control over nanophotonic focusing, leading to advancements in various applications such as imaging, sensing, and integrated photonics.

Chapter 5

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