

# Chapter 1

## Introduction and Motivation

*Chapter 1 presents an introduction to optical fiber, the light propagation principle and types of optical fibers. An extensive view of surface plasmons and the technique of surface plasmon resonance for different configurations have been presented in this chapter. Moreover, I have explored into the topic of optical fiber sensors and explored their different types. Additionally, I have examined the finite element method (FEM) as a technique for modeling the structure of optical fiber sensors, specifically utilizing the COMSOL Multiphysics software. Towards the end of the chapter, I have presented a literature survey and discussed the motivation behind the thesis work.*



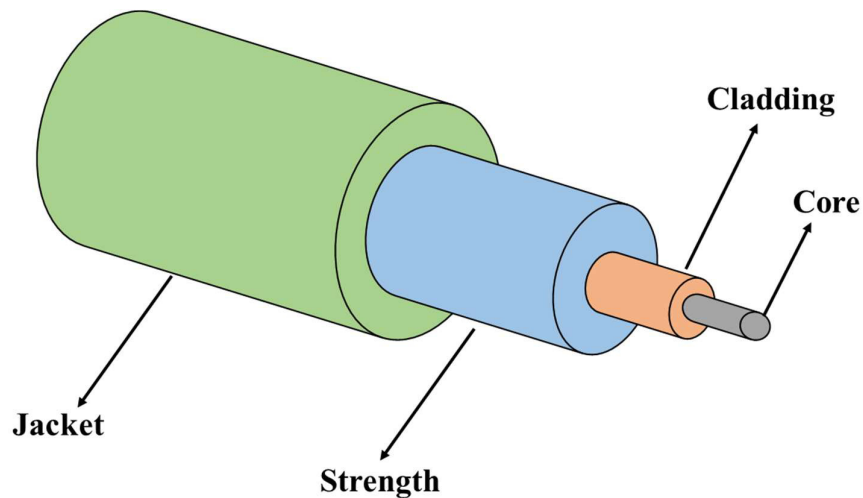
### 1.1 Background

In the past three decades, the optical electronics and fiber optic communication industries have expanded rapidly. Various beneficial products, including barcode scanners, compact disc players, optical switching devices, laser printers, laser pointers, and organic light-emitting diodes have been enhanced by the optical electronics industry<sup>1</sup>. Fiber optics is one of the primary technologies in the era of optics and photonics that was first utilized to transmit information over a long distance as pulses of light through the optical fiber. Since then, beginning with the arrival of the first low-loss, single-mode waveguide in the early 1970s, there have been numerous technological advancements. In 2009, the scientist C. K. Kao, recipient of the Nobel Prize in Physics, proposed for the first time the application of fiber optics in data communication<sup>2</sup>. In parallel with these advancements, optical fiber sensor technology is also developing at an equivalent pace<sup>3-6</sup>. The significant fascination with optical fibers for their utilization in sensing applications can be credited to a multitude of remarkable benefits, including their lightweight characteristics, flexibility, and compact size. Due to their dielectric nature, they are suitable for use in hazardous environments. They are electromagnetic interference-resistant. Their uses in these areas enable measurements of a variety of physical and chemical parameters, including refractive index, temperature, pH, humidity, rotation, pressure, strain, acceleration, magnetic field, electric field, concentration, vibration, acoustics, viscosity, and linear and angular positions<sup>7-21</sup>.

### 1.2 Optical fiber theory

Optical fiber is an information transmission tool that utilizes light pulses to transmit data through a material such as fused silica or plastic fiber. It has a cylindrical shape. It employs the theory of total internal reflection in order to transmit light without loss. The core is composed of a high refractive index (RI) dielectric material such as germanium (Ge)-doped

silica. On the other hand, the cladding is made of a dielectric medium with a lower RI, for example, fused silica and fluorine-doped silica. The core-cladding formation is safeguarded by an additional buffer and jacket, which serve to enhance the mechanical strength of the optical fiber. Typically, buffers are made of fluoropolymers, while jackets are constructed using UV radiative robust materials<sup>22-24</sup>. Figure 1.1 represents the general structure of the optical fiber.



**Fig. 1.1** Optical fiber typically structure

### 1.2.1 Light propagation principle

The propagation of light through the core of an optical fiber can be understood with the help of total internal reflection (TIR). The incident angle is called the critical angle  $\theta_c$ . When the angle of incident  $\theta_i$  is more than a critical angle  $\theta_c$  light rays will return to the same denser medium. This phenomenon is called total internal reflection (TIR). A complete process of TIR is mentioned in figure 1.2.

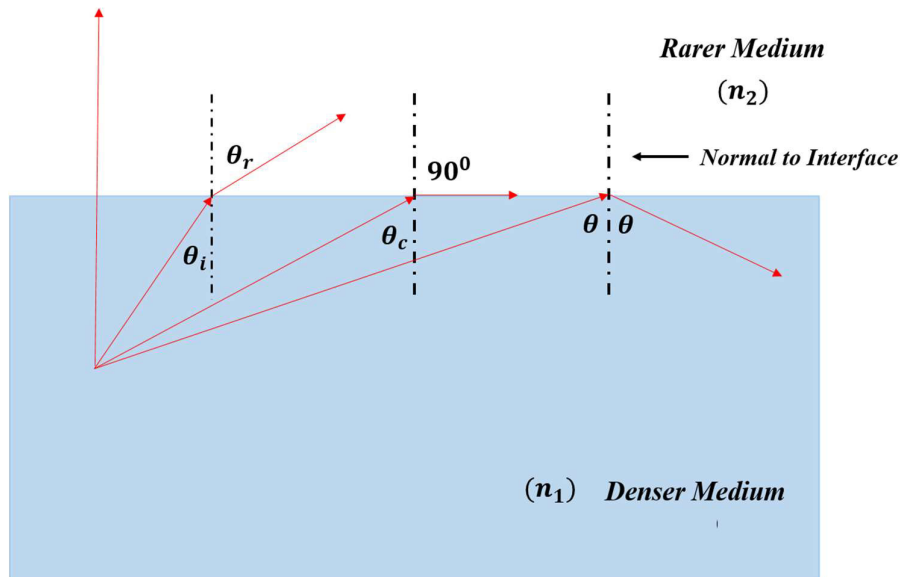


Fig. 1.2 Light refraction at different incident angles

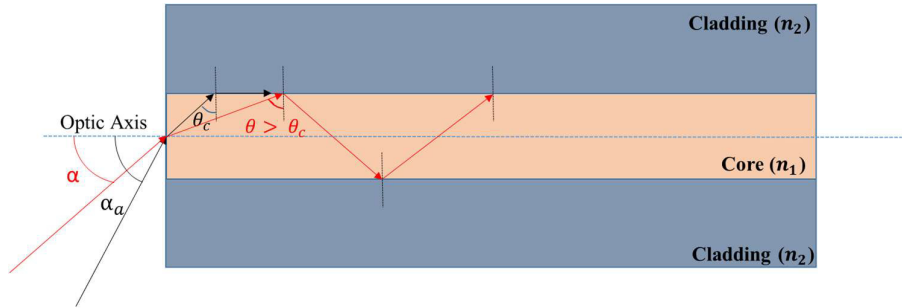
The same phenomenon occurs in optical fiber, where the core has a higher refractive index than the cladding refractive index. When the light incident at a particular angle greater than the critical angle at the boundary of core–cladding, light is reflected in the core and TIR takes place and it is guided through the fiber core with continuous reflections<sup>25</sup>. Apart from a necessary condition of TIR, optical fiber has some other parameters, such as the diameter of the core, numerical aperture, acceptance angle, the refractive index of different core and cladding section materials, and the number of modes. These are also essential factors for the light guidance mechanism through the core of the optical fiber.

### 1.2.2 Numerical Aperture

When a light ray incident at the axis of optical fiber from an external medium of refractive index ( $n_a$ ), at an angle ( $\alpha$ ) less than the acceptance angle ( $\alpha_a$ ) then only TIR inside the optical fiber is possible. The required condition of propagation of light through fiber core in terms of numerical aperture is mentioned in equation 1.1.

$$n_a \sin(\alpha_a) = \text{Sqrt}(n_1^2 - n_2^2) \quad (1.1)$$

Where  $n_1$  ,  $n_2$  ,  $n_a$  are the refractive index of the core region, cladding region, and external medium and  $\alpha_a$  is the half coen angle, respectively. Figure 1.3 depicted the the propagation of light through core of fiber.



**Fig. 1.3** Light propagation in the fiber core by multiple TIR.

### 1.2.3 Optical fiber modes

When an electromagnetic wave propagates through the core of the optical fiber, it contains electric and magnetic field components. These components are mutually perpendicular to each other as well as perpendicular to the direction of propagation of EM wave propagation direction. The term “modes” in optical fiber is defined as the distribution of fields inside the optical fiber core<sup>26</sup>. The number of modes depends on the size of the core diameter, operating wavelength, and refractive index of the core material.

In optical fiber, optical modes are the solution of following Maxwell's wave equation which is also known as Helmholtz equation given by<sup>27</sup>

$$\nabla^2 \vec{E} + n^2(\omega)k_0^2 \vec{E} = 0 \quad (1.2)$$

These modes propagate throughout the fiber with proper boundary conditions and spatial distribution. Basically, there are two types of guided modes that exist inside the optical fiber depending upon their geometrical structure, such as the size of core diameter: (i) single mode optical fiber (SMF) and (ii) multimode optical fiber (MMF). In a single-mode optical fiber, the diameter of the core is 9  $\mu\text{m}$ , while the diameter of the cladding is approximately 125  $\mu\text{m}$ . In a multimode optical fiber, the large core diameter (about 50  $\mu\text{m}$ ) allows multiple modes to propagate inside the core throughout the fiber length.

The "V – Number" parameter differentiates between single mode and multimode fibers. The normalized parameter V – Number is given by the following equation

$$V = \frac{2\pi a}{\lambda} \times NA \quad (1.3)$$

In the above equation, ( $a$ ) denotes the radius of the fiber's core, ( $\lambda$ ) is the operating wavelength, and  $NA$  is the numerical aperture given by eq. (1.2).

### 1.2.4 Classification of optical fibers

There are several types of optical fibers, each designed for specific applications and performance characteristics. Based on the number of modes, Optical fibers can be categorized in two types: single-mode fiber (SMF) and multimode fiber (MMF). SMFs are typically step-index (SI) fibers, whereas MMFs can be further classified into two categories: SI-MMF (Step-Index Multi-Mode Fibers) and GI-MMF (Graded-Index Multi-Mode Fibers).

#### 1.2.4.1 Single mode step index fiber (SM - SIF)

In this type of fiber, light mode propagates along the axis of the fiber in a straight line path. This mode is the fundamental mode supported by single-mode fiber. It is because the core diameter is very thin, approximately 8 ~ 12  $\mu\text{m}$ , and the external diameter of the cladding

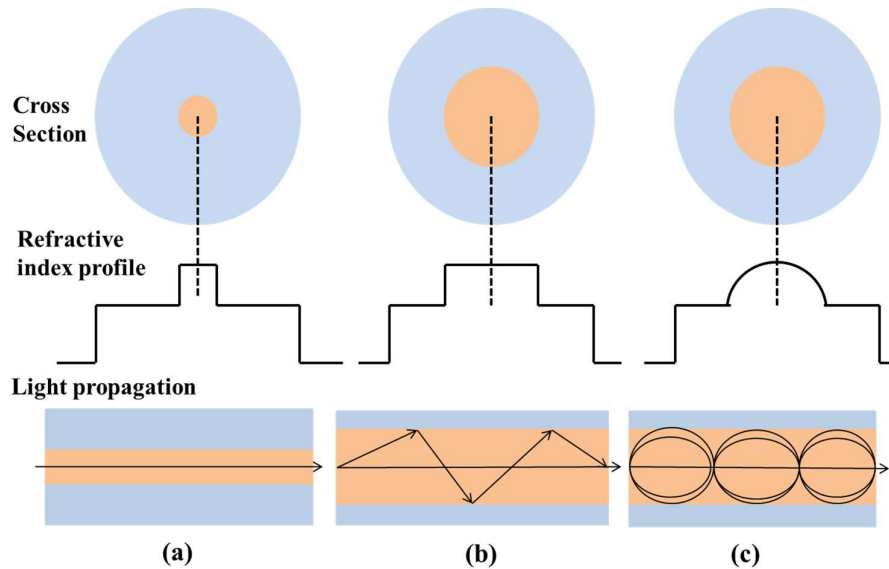
portion<sup>27</sup> is approximately 125  $\mu\text{m}$  shown in Fig. 1.4(a). There is a selection of different materials in the core and cladding portion. The core is composed of germanium-doped silica material, while the cladding comprises pure silica material.

### 1.2.4.2 Multi-mode step index fiber (MM - SIF)

A multimode step-index fiber resembles a single-mode step-index fiber, except the core diameter size is 50 ~ 100  $\mu\text{m}$  which is comparatively larger than the core diameter size of a single-mode step-index fiber. The cladding diameter is approximately 150 ~ 250  $\mu\text{m}$  depicted in Fig. 1.4(b). MM – SIF allows a finite number of modes to propagate in the fiber's core in which higher modes acquire the different zig-zag path inside the core. There is a bit of time delay between the low order mode and high order mode while reaching the end of the fiber because high order mode has a zig-zag path, so they have a long way to cover while low order mode propagates along the axis of the fiber core with a shorter path<sup>27</sup>.

### 1.2.4.3 Multi-mode graded index fiber (MM - GIF)

A graded index fiber is a type of fiber that has a variable refractive index-based core region. The refractive index variation in the core is periodic, with a high refractive index at the center and a gradually decreasing refractive index value with a radius on both sides to the center having minima at the core-cladding interface displayed in Fig. 1.4(c). The diameter of the core-cladding of graded index fiber is the same as the diameter of core-cladding of step index fiber<sup>27</sup>.

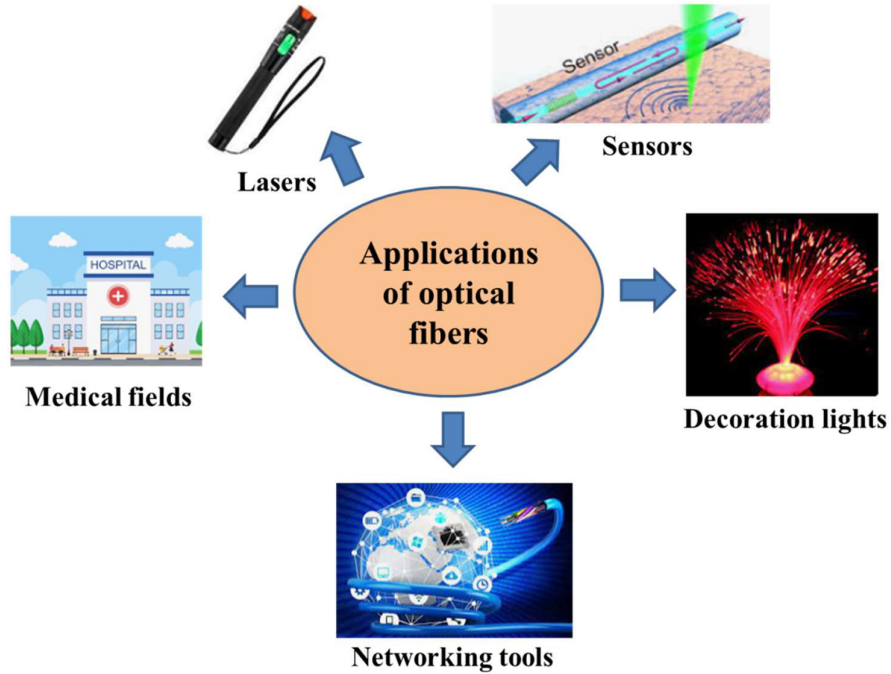


**Fig. 1.4** Cross-section, refractive index profile and light propagation diagrams for **(a)** single mode fiber (SMF), **(b)** step-index multimode fiber, and **(c)** graded-index multimode fiber.

### 1.2.5 Applications of optical fiber

Optical fiber is one of the leading technologies in the field of optics. It has many applications such as sensor devices, optical switching devices, laser printers, laser pointers, and organic light emitting diodes, and I discuss some of them in my work. When a number of fibers are bunched together to form a flexible bundle of fibers that is grounded and polished at both sides and aligned such that the order of fibers in this bundle is identical at both ends, such a fiber bundle is known as a coherent bundle. Using this coherent bundle, images can easily be carried point by point from one end of the fiber to the other end. This technique is widely used in the medical field for endoscopy<sup>28</sup>. The communication system based on optical fiber is much similar to traditional electronic communication systems. In electronic communication, the electric signal is transferred through copper cable wire or waveguides. In modern technology, copper cable wire has been replaced with optical fiber, and the electric signal is converted into a light signal. The optical fiber cable enhances the communication

speed compared to the old communication system. Various optical fiber applications are depicted in Fig. 1.5.



**Fig. 1.5** Applications of optical fibers in various fields.

### **1.3 Surface Plasmon**

Over the past few decades, surface plasmon resonance (SPR) has made significant contributions to various research fields. In the early stages of research on SPR, Wood observed an unusual pattern of bright and dark bands in the reflection spectrum in 1902. This phenomenon occurred when plane-polarized light was incident on a mirror that had a diffraction grating on its surface<sup>29</sup>. Zenneck made significant theoretical contributions by studying the generation of radio frequency surface electromagnetic waves that propagate at the interface between two media. Here, one of the media involved was a lossless medium, while the other medium was a lossy dielectric or metal medium<sup>30</sup>. In 1909, Somerfield

conducted further studies on the surface waves that occur at the interface between a metal and a dielectric material. He observed that the amplitudes of the field associated with the surface waves at the metal-dielectric interface change reciprocally with the square root of the distance from the interface<sup>31</sup>. In a later development, Fano provided a theoretical explanation for the observation made by Wood in 1902. He postulated that the pattern of bright and dark bands observed in the reflection spectrum was due to the excitation of surface waves on the surface of the diffraction grating<sup>32</sup>. In 1957, the excitation of surface plasmons (SPs) at metallic surfaces was described analytically<sup>33</sup>. In 1959, Thurbadar conducted a study in which a downfall in reflectance was observed when metallic thin films were deposited on a substrate. However, he could not connect the surface plasmons with this phenomenon<sup>34</sup>. In 1960, Powell and Swan conducted a study on the excitation of surface plasmons at the interface between metal and dielectric materials using electrons<sup>35</sup>. Stern and Ferrell found an important discovery regarding the coupling of surface plasmons with electromagnetic waves that propagate at the metal surface<sup>36</sup>. In 1959, Otto provided an explanation of the Thurbadar observations. He explained that the phenomenon of surface plasmons getting excited is due to the loss in reflectivity of the reflected light in the attenuated total reflection<sup>37</sup>. The Otto configuration is considered less suitable from a practical viewpoint due to the presence of a fixed air gap between the base of the prism and the metallic layer. The Otto configuration was modified by the Kretschmann configuration<sup>38</sup>. According to the Kretschmann configuration, a thin metal layer is deposited on the prism base, and the sample medium (dielectric) is placed in direct contact with the plasmonic metallic layer. The refractive index of the analyte sample can be determined using this method.

In the method, the detection of a sharp SPR minimum in the reflection spectrum is seen. Several prism-based sensors have been reported for the sensing of various parameters such as refractive index, temperature, pH, and many others<sup>39-43</sup>. One side, prism-based devices offer

certain advantages such as, level free detection, real-time monitoring, fast response and etc. but on the other side, it also has several drawbacks. One of the major drawbacks of prism-based devices is their bulky size. Furthermore, the optimization of prism-based devices on a large scale becomes challenging due to the presence of numerous optical and mechanical components. These drawbacks can be mitigated by replacing the prism with the optical fiber core because the optical fiber core has a smaller diameter. Furthermore, miniaturization of the SPR probe is achievable. Additionally, optical fibers offer advantages such as larger bandwidth, ability for online monitoring, and the remote sensing capabilities. Therefore, fiber optic SPR sensors offer simplified optical design and real time sensing capability. Considering these unique benefits of optical fibers, significant research efforts have been dedicated to advancing fiber optic SPR based sensors. A thin plasmonic metallic layer is directly deposited over the unclad part of the fiber core. Generally, a wavelength interrogation scheme is utilized in SPR sensors. In this technique, a range of wavelengths from a white light source is directed into the fiber at a fixed angle of incidence. On the other hand, in an angular interrogation scheme, the wavelength of the incident ray is fixed while the incidence angle is varied.

### 1.3.1 General scenario of surface plasmons

The band theory of solids is a fundamental framework that explains numerous properties of the solid state. However, the plasma model represents an alternative approach that can explain various properties of the solid state in a distinct manner. The conduction electrons in metals can be conceptualized as an electron gas with a high density of approximately  $10^{23}$   $\text{cm}^{-3}$ . In comparison to the mass of the free electrons, the positive ions in metals are considered to have infinitely large mass. According to the jellium model<sup>44</sup> the positive ions in metals can be effectively replaced by a positive constant background charge. Nevertheless, in a conductor, the total charge density remains zero. If the density of free electrons in a

conductor is locally reduced by applying an external electric field, the negatively charged free electrons are no longer fully shielded by the positive ion background. As a result, they begin to experience an attraction towards the positive ion background. Consequently, the free electrons begin to migrate towards the positive region and accumulate with a density higher than necessary for local charge neutrality. At this stage, the Coulomb repulsion between the moving free electrons acts as a restoring force, leading to motion in the opposite direction. The combined effect of these two forces, the attractive driving force and the repulsive restoring force, gives rise to longitudinal oscillations among the free electrons. These oscillations, referred to as plasma oscillations, involve density fluctuations that propagate throughout the entire volume of the metal. The frequency of these plasma oscillations is determined by the expression:

$$\omega_p = \text{Sqrt} \left( \frac{4\pi n e^2}{m_0} \right) \quad (1.7)$$

Where  $m_0$  is the mass of an electron,  $n$  is the density of free electrons, and  $e$  is the elementary charge<sup>45</sup>.

The coherent oscillations of free electrons on the metal-dielectric interface are known as surface plasmons. Surface plasmons are propagating electron density waves that occur at the interface between a metal and a dielectric. They can also be understood as electromagnetic waves tightly bound to the interface. Let's consider a configuration where a metal layer and a dielectric layer are stacked along the  $z$ -axis, and the direction of propagation of the surface plasmon wave is along the  $x$ -axis.

The surface plasmon wave associated field can be expressed as:

$$E = E_0 e^{i(xk_x + zk_z)} \quad (1.8)$$

Signs - and + are for  $z \leq 0$  and  $z \geq 0$  respectively. The wave vector, parallel to the x-axis, is given as,  $k_x = \frac{2\pi}{\lambda_p}$ ;  $\lambda_p$  represents the plasma wavelength<sup>45</sup>.

By applying the boundary conditions at the interface between the metal and dielectric layers, the dispersion relation for the surface plasmon wave can be derived as,

$$k_{sp} = k_x = \frac{\omega}{c} \left( \frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s} \right)^{1/2} \quad (1.9)$$

There, frequency of the incident light is denoted by  $\omega$ , and  $c$  represents the speed of light in vacuum. The dielectric constants of the metal and sensing analyte dielectric are represented by  $\epsilon_m$  and  $\epsilon_s$ , respectively.

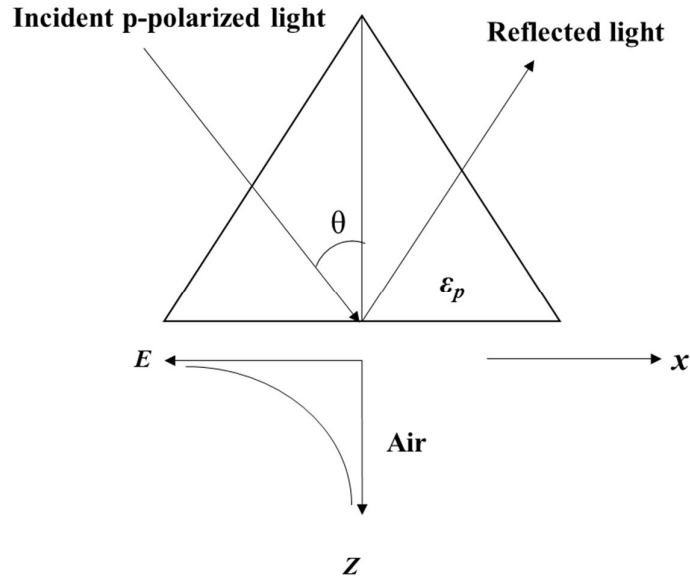
#### 1.4 Method of surface plasmons excitation

The propagation constant ( $K_{inc}$ ) of light in the air can excite the surface plasmons, and its expression is given by,

$$K_{inc} = \frac{\omega}{c} \quad (1.10)$$

Here,  $c$  and  $\omega$  represent the speed of light in vacuum and frequency of the incident light respectively. For the excitation of surface plasmons, the propagation constant of the incident light should be equal to the propagation constant of the SPW<sup>46</sup>. Since the SPW is p-polarized, it is essential to use incident light that is also p-polarized for the excitation process. Due to the positive dielectric constant of the sensing analyte dielectric medium ( $\epsilon_s > 0$ ) and the negative dielectric constant of the metal ( $\epsilon_m < 0$ ), the propagation constant of the SPW is  $k_{sp}$  always higher than the propagation constant of the incident light for a given wavelength. Therefore, direct light is incapable of exciting surface plasmons. Thus, in order to excite a SPW at a specific wavelength, additional energy or momentum ( $k$ ) needs to be imparted to the incident light. Various techniques have been utilized to enhance the

momentum or energy of the incident light, facilitating the excitation of SPs. In 1968, Otto made the first attempt to excite surface plasmon waves using a prism to generate the evanescent wave<sup>37</sup>. The evanescent wave intensity behavior is shown in Fig.1.6. This technique was later refined and modified by Kretschmann<sup>47</sup> as discussed in the next section.



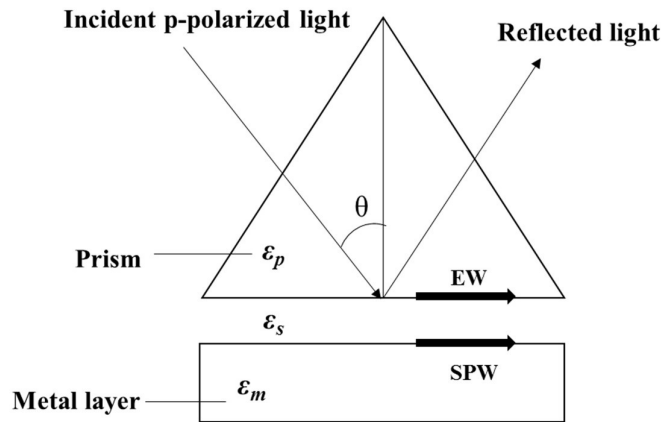
**Fig. 1.6** Establishment of an evanescent wave at the interface between a prism and air at  $\theta > \theta_c$

#### 1.4.1 Otto configuration

Otto utilized a prism configuration, as illustrated in Fig. 1.7, to excite SPs. In this Otto configuration<sup>48</sup>, a metal film is positioned beneath the base of the prism at a specific distance. The narrow gap between the prism and the metal film is filled with the sensing analyte sample under investigation. When p-polarized light is incident at the base of the prism at an angle  $\theta$  greater than the critical angle ( $\theta_c$ ) at the prism (glass)-air interface, an evanescent wave (EW) is generated at the base of the coupling prism. The propagation constant of this evanescent wave, which is along the interface, can be given by:

$$k_{EW} = \frac{\omega}{c} \sqrt{\epsilon_p} \sin(\theta) \quad (1.11)$$

Here,  $\epsilon_p$  represents the dielectric constant of the material composing the prism<sup>49</sup>. If the wave vectors of the EW and the SPs are same, the SPW is excited at the metal-dielectric interface. This results in a dip in the intensity of the reflected light. However, it can be challenging to maintain a small gap between the prism and the metal film, which is a limitation for easy implementation. As a result, Kretschmann modified the Otto configuration to address this issue<sup>50</sup>.



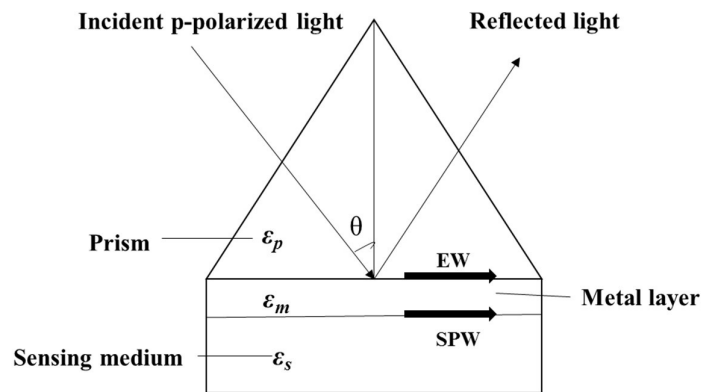
**Fig. 1.7** Otto configuration

### 1.4.2 Kretschmann configuration

The Kretschmann configuration is a widely used method for generating surface plasmons and is considered the simplest approach. In this technique<sup>50 51</sup> a thin metal film with a permittivity  $\epsilon_m$  is placed in contact with a prism made of a material with a high dielectric constant ( $\epsilon_p$ ). The prism is surrounded by another sensing dielectric medium with a lower dielectric constant  $\epsilon_s$  ( $\epsilon_s < \epsilon_p$ ). The phase-matching condition for the coupling between the evanescent wave and surface plasmon can be expressed as follows<sup>49</sup>

$$\frac{\omega}{c} \sqrt{\epsilon_p} \sin(\theta) = \text{Re}(k_{sp}) \quad (1.12)$$

Surface plasmon resonance (SPR) occurs when there is a transfer of energy or momentum between the EW and the SPs. Prism-based SPR sensing devices are subject to certain limitations, including their relatively large size due to the presence of multiple mechanical and optical components. Moreover, these sensors are not suitable for remote sensing applications, restricting their practical utility in certain scenarios. In present times, optical fibers have replaced prisms in SPR-based sensor devices. Optical fibers offer the additional advantage of miniaturizing the SPR probe. Furthermore, using optical fibers can be advantageous when dealing with analyte samples that are available in small quantities and are costly.



**Fig. 1.8** Kretschmann configuration

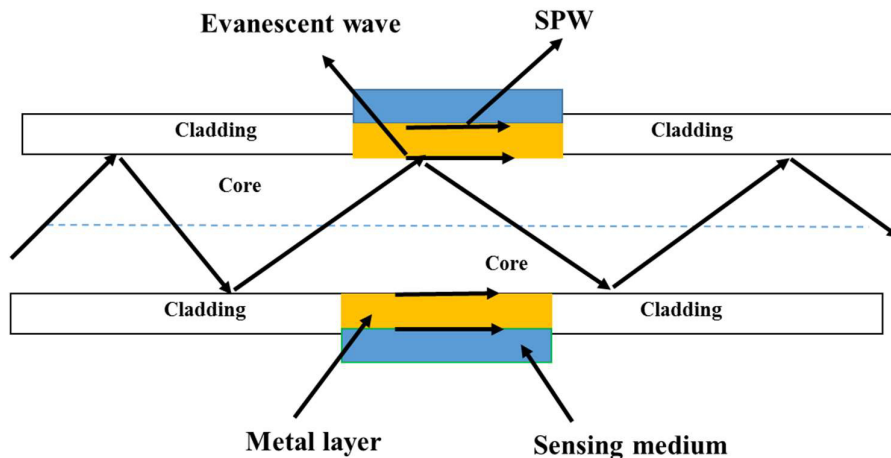
### 1.5 Optical fiber SPR sensing based on Kretschmann configuration principle

The resonance condition in SPR technique is significantly influenced by the wavelength of the incident light beam, the angle of incidence, and the dielectric functions of both the dielectric material and the metal. When the angle of incidence is varied while keeping the wavelength constant in an SPR technique, a sharp dip in the intensity of the reflected light is observed at a specific angle. This method of detecting changes in the refractive index by analyzing the angular position of the dip is known as angular interrogation. In wavelength interrogation, the angle of incidence is kept constant while the wavelength of the incident

light is varied. In this method, resonance occurs at a specific wavelength. Changing the values of the resonance parameter (angle of incidence or the wavelength) are directly influenced by the refractive index of the dielectric medium surrounding the metal film. By changing the refractive index of the medium surrounding the metal film, the value of the resonance parameter is changed accordingly. This change in the resonance parameter allows for the detection and measurement of variations in the refractive index of the surrounding medium.

From the preceding discussion, it is evident that for the excitation of SPs, the wave vector of the incident light must be matched with the SPs. Additionally, direct light alone is incapable of exciting SPs.

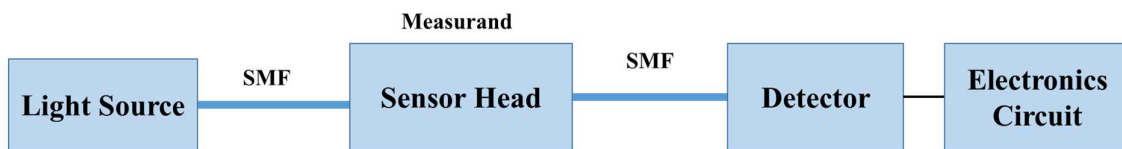
In the Kretschmann configuration, the wave vector of the incident light is enhanced by utilizing a high refractive index glass prism, which generates EW through TIR at the interface between the prism and the metal. The kretschmann principle based optical fiber SPR sensing configuration is demonstrated by Fig.1.9.



**Fig. 1.9** Optical fiber sensing configuration based on Kretschmann principle.

## **1.6 Optical fiber sensor**

Utilizing the properties of light propagation through an optical fiber, an optical fiber sensor is a device designed for physical, chemical, or biological sensing. It is based on the principle that on changing refractive index of the surrounding medium of optical fiber, transmission of light through optical fiber changes. By detecting and quantifying these changes, the sensor enables the measurement of various parameters with high precision and sensitivity. Optical fiber sensor set-up arrangement has light source (Laser or LED) at input, optical fiber link, sensor head, optical signal detection device such as OSA, and results display device. Fig. 1.10 is depicted the optical fiber complete set-up arrangement.



**Fig. 1.10** Set-up arrangement of optical fiber sensor.

### **1.6.1 Sensing mechanism-based optical fiber sensors**

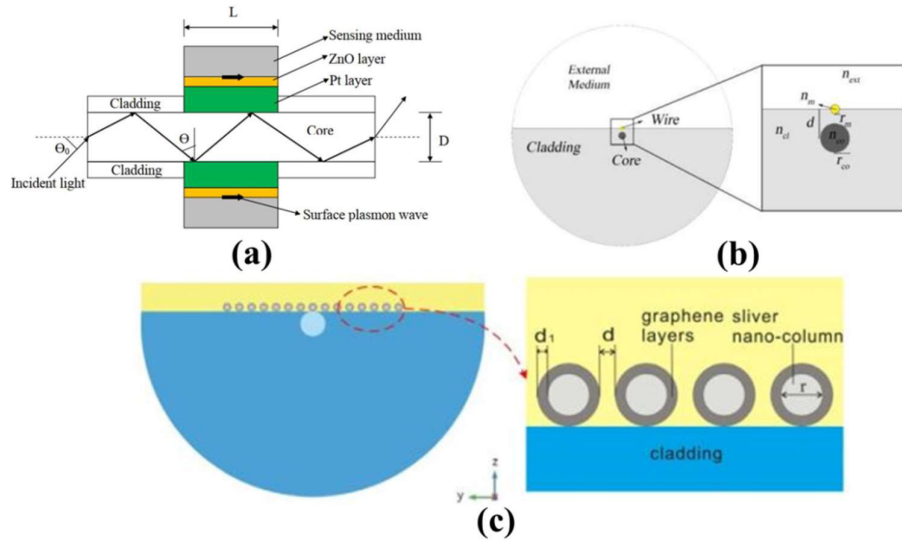
Optical fiber sensors can be classified into two types based on the sensing mechanism for analyte detection:

- I. External Sensing Mechanism
- II. Internal Sensing Mechanism

#### **1.6.1.1 Optical fiber sensor based on external sensing mechanism**

In this mechanism, known as the external sensing configuration, the sensing analytes are placed outside the optical fiber head. On the basis of this mechanism, distinct optical fiber sensors structures for a wide range of applications have been presented, such as plasmonic

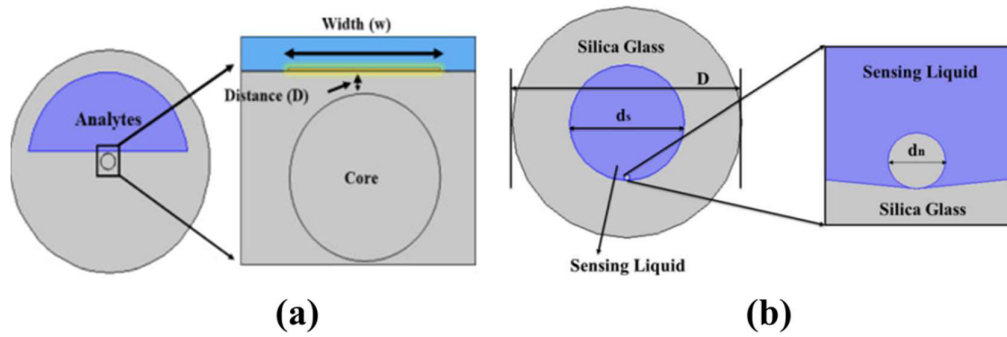
material thin layer coated optical fiber sensors, metal nanowire utilized optical fiber sensor, metallic grating-based optical fiber sensor, and etc.



**Fig. 1.11** External sensing mechanism based optical fiber sensor, such as (a) thin layer based-sensor<sup>52</sup> (b) nanowire-based sensor<sup>53</sup> (c) grating-based sensor<sup>54</sup>

### 1.6.1.2 Optical fiber sensor based on internal sensing mechanism

In the internal sensing mechanism-based optical fiber sensor, the sensing analytes are placed either within the hollow core or inside the cavity of the fiber itself. There is no requirement for placing the analytes in an extra container. Optical fiber sensors based on this mechanism have a variety of structures for various purposes.



**Fig. 1.12** Internal sensing mechanism based optical fiber sensor such as **(a)** thin layer based-sensor<sup>55</sup> **(b)** nanowire-based sensor<sup>56</sup>

### 1.6.2 Based on applications Optical fiber sensor

Optical fiber sensors have garnered significant interest due to their versatile structure design and various advantages, as discussed earlier. These sensors have found applications in diverse fields such as chemical laboratories, environmental monitoring, food processing, disease diagnosis, structural health monitoring, and many more. Optical fiber sensors are generally classified into three categories based on their field of application. In the subsequent subsections, I will briefly discuss some important applications of optical fiber sensors within each of the aforementioned categories. Optical fiber sensors can be categorized into three sections based on their application:

- I. Physical sensor
- II. Chemical sensor
- III. Bio sensor

#### 1.6.2.1 Physical sensor

Optical fiber sensors that are employed for detecting physical parameters such as refractive index, temperature, pressure, displacement, curvature, torsion, vibration, electric field, and

more, fall under the category of physical sensors<sup>16 17 57 58 59 60</sup>. These sensors find wide-ranging applications in various fields where precise and accurate measurements of physical parameters. Optical fiber-based refractive sensors exhibit high sensitivity and efficiency, making them applicable in various industries. In the food and beverage industry, these sensors are valuable for quality control purposes. They also find application in the chemical industry for accurate measurement of refractive index and in biological pathology for the identification of biomolecules. Optical fiber based temperature sensors demonstrate exceptional efficiency in accurately measuring temperature, various furnace applications, even in demanding environmental conditions prevalent in power generation operations, steel rolling lines, and the development of welding equipment. In civil structures such as bridges, pipelines, tunnels, and buildings, PCF sensors designed for strain, curvature or bend sensing, vibration sensing, and electric and magnetic field sensing are instrumental in various applications. These sensors are utilized for strain and pressure monitoring, as well as temperature control.

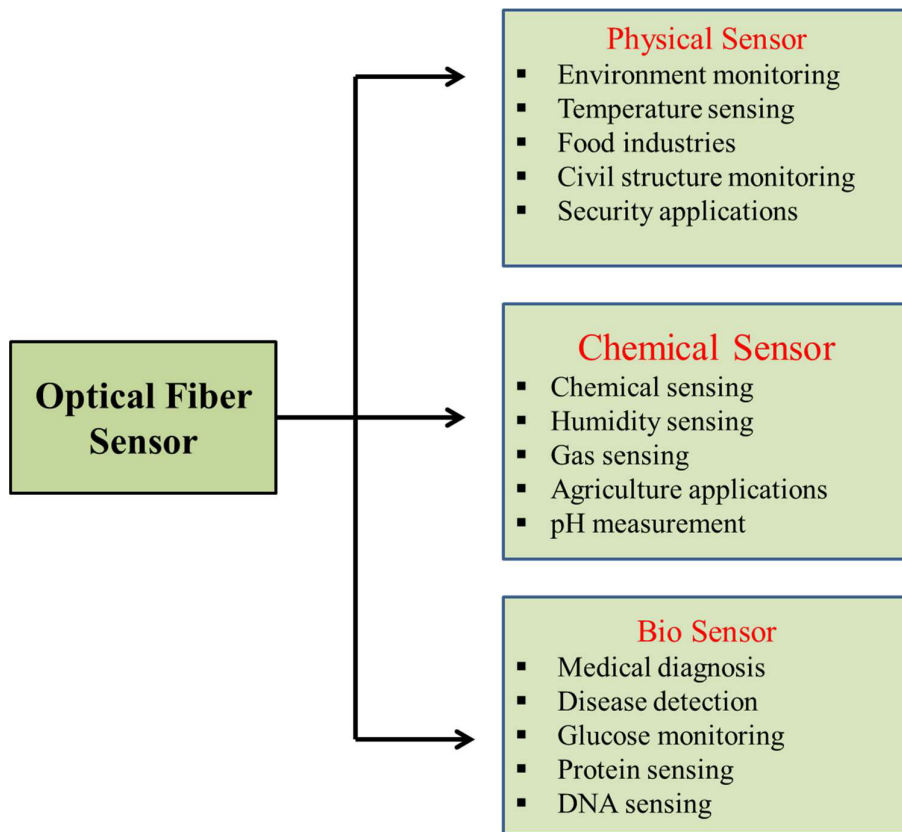
### 1.6.2.2 Chemical Sensor

Optical fiber sensors are utilized for detecting chemical parameters, including pH, impurities in water and gas content. These sensors are classified as chemical sensors and find application in various fields. Highly applicable in gas sensing, optical fiber sensors with different designs are efficient in detecting the leakage or emission of harmful gases like hydrocarbons and hydrogen. These sensors useful in various fields, including industries thermal power stations, homes, mines, motor vehicles, workplaces, and chemical plants. Optical fiber gas sensors demonstrate their usefulness in various applications such as chemical industries and pollution control measurements<sup>61 62 63 64</sup>. Another type of chemical sensor, optical fiber humidity sensors find efficient applications in a wide range of fields. These sensors are effectively applicable in environmental monitoring, food processing, air

conditioning, horticulture, structural monitoring, museums, greenhouses, humidors, and industrial spaces.

### **1.6.2.3 Bio Sensor**

Optical fiber sensors, which have the capability to detect biological analytes such as proteins, glucose, DNA<sup>65 66 67 68 69</sup> and more, are classified as biosensors and find extensive applications in various fields. Among all biosensors, SPR-based optical fiber biosensors are widely recognized and popular. They are particularly favored due to their label-free technique, which enables the real-time detection of biological analytes.



**Fig. 1.13** Applications based optical fiber sensors.

### 1.7 Optical fiber modeling numerical methods

Several numerical methods are commonly utilized for optical fibers modeling such as full vectorial finite element method (FVFEM)<sup>70</sup>, finite difference time domain (FDTD)<sup>71</sup>, finite difference frequency domain method (FDFD)<sup>72</sup> and plane wave expansion method<sup>73</sup>. Each method has its limitations, along with its own merits and demerits. Researchers and engineers can leverage these numerical methods to perform accurate simulations and analysis of a wide range of optical fiber properties. These include modal behavior, dispersion, nonlinearity, and interactions with external factors. By utilizing these methods, they can optimize fiber designs, gain insights into complex phenomena, and drive the development of advanced optical fiber devices and systems. I have chosen the FVFEM for my research work due to its notable advantages and efficiency in analyzing complex structures such as optical fibers<sup>70</sup>.

#### 1.7.1 Full vectorial finite element method

The FEM is a numerical technique utilized to solve partial differential equations and analyze the behavior of complex structure. The FEM was first proposed in 1940 and later utilized in structural designing and analysis in the various fields starting from the 1950. Compared to other numerical methods, the main advantage of FEM is the minimum computational time required for analyzing complex structures<sup>70</sup>.

In the FEM, designed structure is divided into smaller finite elements. The behavior of the system is approximated within these elements, where each finite element represents a portion of the domain. Within each element, the governing equations, such as the wave equation for

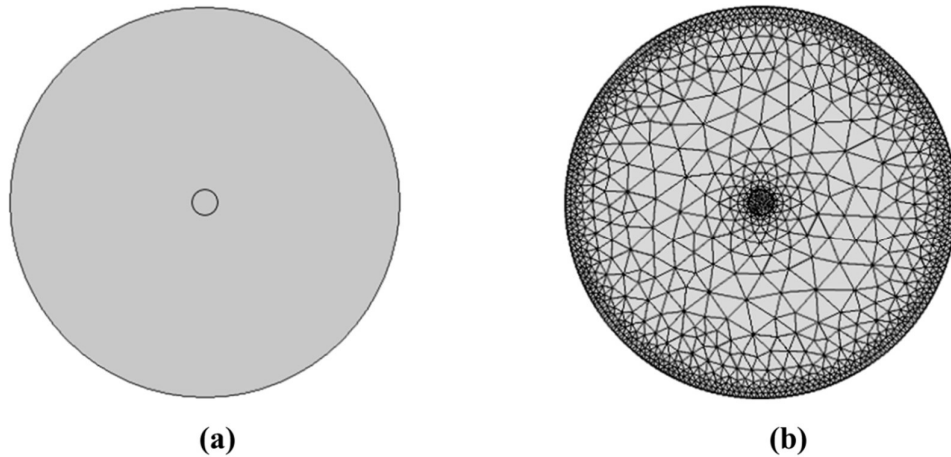
light propagation, are discretized and solved. The FEM allows for the modeling and analysis of complex structures, by following steps:

- Designed the geometry of the structure and selected the materials.
- The structure should be divided into smaller, finite elements, with each element representing a portion of the structure.
- Formulate the governing equations for each element based on the underlying physics and the type of analysis being conducted.
- To obtain the global equations for the entire structure, assemble the element equations.
- Apply the prescribed boundary conditions to the global equations after assembling them.
- To determine the unknowns, such as effective indices, temperatures, stresses, displacements, by solve the system of equations.
- Analyze and interpret the results obtained from the solution.

### **1.7.1.1 Numerical finite element method for optical fiber using COMSOL Multiphysics**

The optical fiber sensor design modeling and numerical simulations presented in this thesis are based on the finite element method (FEM) and performed utilizing the COMSOL Multiphysics software. The modeling and simulation process of an optical fiber sensor can be completed several steps. First, I design the structure of the optical fiber sensor, which includes its dimensions, core, cladding, and any additional layers. There is significant freedom to choose predefined materials and customize the optical properties according to the requirements. This includes selecting the desired material's refractive index (RI),

permeability, conductivity, dispersion, and other optical properties. In the next step, we select the material for each domain and create a finite element mesh to discretize the cross-section optical fiber structure. In my work, I have chosen triangular elements meshing for achieving accurate solutions, shown in Fig.1.14. Applying structural symmetry in numerical simulations not only allows for computational efficiency but also helps improve the accuracy of the results<sup>70</sup>.



**Fig. 1.14 (a)** Designed optical fiber sensor by COMSOL Multiphysics software **(b)** Model after mesh creation

To minimize scattering loss, I have selected the Perfectly Matched Layer (PML) boundary condition. Furthermore, the Maxwell's equations are discretized for each meshing element, resulting in a set of elementary matrices corresponding to each element. These elementary matrices are combined to form a global matrix system, which is utilized to analyze the structure. In the final results, the effective index ( $n_{eff}$ ) real and imaginary parts are numerically computed. The computed  $n_{eff}$  can be utilized to accurately calculate the desired optical parameters of the designed optical fiber. Simulation process complete flow chart is shown in Fig. 1.15.

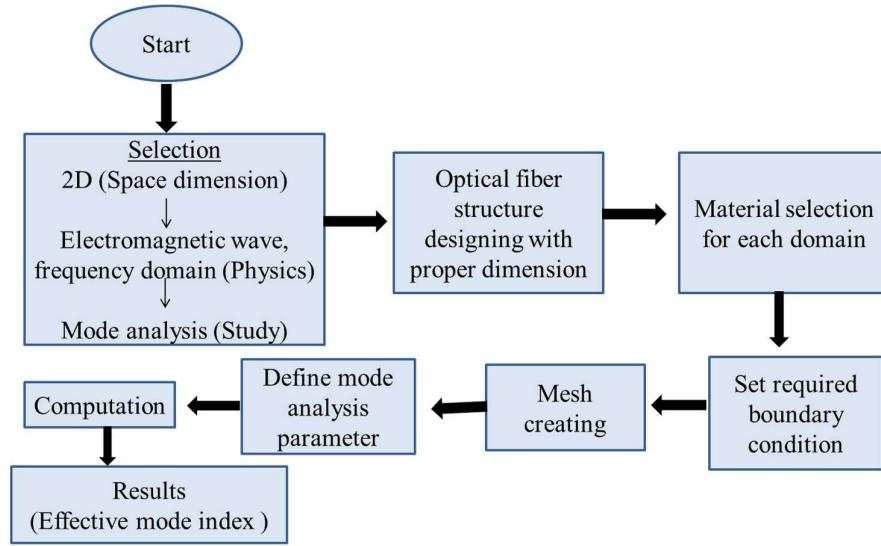


Fig. 1.15 Simulation process complete flow chart

## 1.8 Some principle and performance parameter with theoretical formulation

In this section, a detailed discussion has been presented on the theoretical formulation of properties, principles, and parameters that are considered and analyzed in order to design successful optical fiber SPR sensors and to assess their sensing performance.

### 1.8.1 Sellmeier's dispersion equation

The propagation of light is influenced by two key factors: the refractive index (RI) of the medium through which it travels and the frequency or wavelength of the light itself. In 1871, Wolfgang Sellmeier reported a significant research that the refractive index of a material is influenced by the wavelength of the propagating light<sup>74</sup>. The refractive index of the fiber core and cladding materials is calculated by the following sellmeier's equation:

$$n(\lambda) = 1 + \left( \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2} + \frac{A_3\lambda^2}{\lambda^2 - B_3} \right)^{\frac{1}{2}} \quad (1.13)$$

Where  $n(\lambda)$  material refractive index at incident light wavelength  $\lambda$ . Sellmeier's coefficients  $A_1, A_2, A_3$  and  $B_1, B_2, B_3$  have different values for different material. Generally,

germanium (Ge) doped silica material is used for fiber core and fluorine (F) doped silica is used for fiber cladding material<sup>75</sup>.

### 1.8.2 Confinement loss of optical fiber

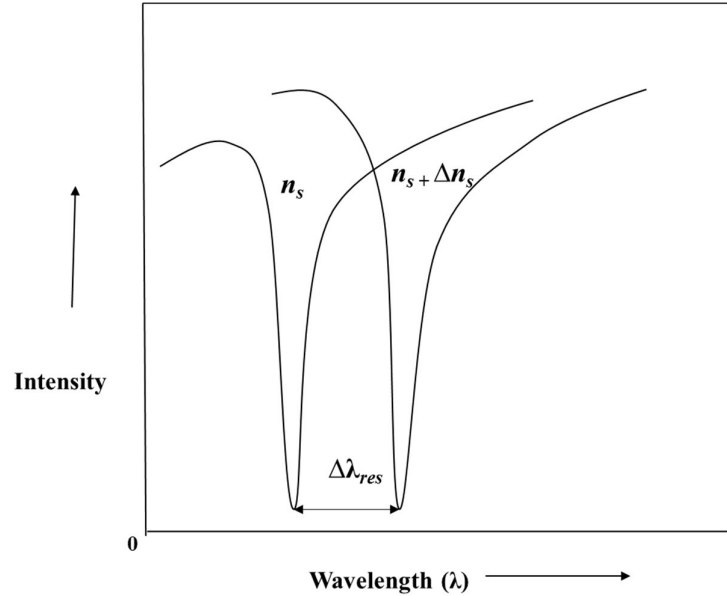
Propagation light is guided inside the fiber core region. Leakage light depends on the imaginary value of effective index of the lossy mode. The confinement loss of leakage light is calculated by the following equation.

$$\alpha = 8.868 \times 10^4 \times \frac{2\pi}{\lambda_0} \times \text{Im}(n_{eff}) \text{ [dB/cm]} \quad (1.14)$$

Here, the symbol  $\lambda_0$  represents the wavelength of light in free space, while  $\text{Im}(n_{eff})$  represents the imaginary component of the effective mode index<sup>76</sup>. Confinement loss depends on the several parameters.

### 1.8.3 Sensitivity

As previously discussed, a change in the refractive index of the sample results in the satisfaction of the resonance condition at different values. In the case of angular interrogation method, even a slight shift in the refractive index  $\Delta n_a$  leads to a corresponding shift in the resonance angle  $\Delta\theta_{res}$ . In contrast, in the wavelength interrogation method, a slight change in the refractive index of the sample medium leads to a shift in the resonance wavelength  $\Delta\lambda_{res}$ . A better-performing SPR sensor is characterized by higher sensitivity, which utilizes as the main performance parameter of the sensor. Fig. 1.16 illustrates two different SPR curves plotted for two dissimilar values of the refractive index in the sensing region.



**Fig. 1.16** Reflected light intensity with the wavelength

As the refractive index is increased by an change  $\Delta n_s$ , the resonance wavelength shifts to a higher value by  $\Delta\lambda_{res}$ . The sensitivity of the sensor in the wavelength interrogation method is determined by the ratio of the variation in resonance wavelength to the variation in refractive index. Mathematically, it can be expressed as<sup>76</sup>:

$$S_\lambda = \frac{\Delta\lambda_{res}}{\Delta n_s} \quad (1.15)$$

### 1.9 Advantage of optical fiber SPR sensor

The numerous benefits stem from two key factors: the fibers being composed of dielectric materials such as fused silica or plastic and propagation of signals within these fibers occurs through "elements" composed of photons rather than electrons.

Optical fiber sensors and systems have successfully demonstrated their numerous advantages and capabilities across a wide range of environments and applications. Presently, fiber optic sensors hold immense potential for applications in sensing condition. The significance of optical fiber sensors in sensing condition applications arises from the following reasons:

- These optical fiber sensors offer several operational advantages over conventional sensors.
- These sensors are constructed from highly durable materials such as fused silica or plastic, which exhibit corrosion resistance and can withstand high tension. This robust construction enhances their longevity and reliability in sensing condition applications.
- These sensors have the capability to be applied to complex surfaces and hard-to-reach areas, such as along sharp corners, or across welds, around the circumference of round objects.
- These sensors provide the flexibility of achieving sensing lengths that span from less than 1 millimeter to kilometers.
- These sensors offer exceptional spatial resolution, allowing for precise and detailed measurements in sensing condition applications.
- These sensors can be utilized in a wide range of pressure conditions, including extreme environments like deep-sea depths or outer space, without the need for adjustments.
- These sensors possess the capability to monitor the composition of gases or liquids with a high level of accuracy.
- These sensors have the capability to simultaneously monitor multiple parameters, leading to a reduction in system cost and complexity.
- These sensors have already achieved cost competitiveness when compared to many conventional sensors.

### 1.10 Literature review

In optical fiber sensing based on SPR, p-polarized light is utilized to excite SPs at the interface of a metal and a dielectric material. The field strength of the Surface Plasmon Wave (SPW) at the metal-dielectric interface undergoes exponential decay. In recent years, SPR sensors have gained significant popularity for their application in studying biological sensing and chemical detection. Due to its unique features, including label-free, real-time and non-invasive detection capabilities, SPR technology highly promising in the field of optical fiber sensors. Indeed, I have previously discussed the utilization of p-polarized light for exciting SPWs at the metal-dielectric interface within sensor structures, along with various configurations and applications.

In this section, I begin with a comprehensive literature survey of optical fiber SPR sensors utilizing various metals thin layers. Following that, I have conducted a thorough literature survey on optical fiber SPR sensors based on nanowires, metal oxides, and hollow cores.

In 2008, M. Kanso et al. published a modeling and experimental discussion based optical fiber SPR sensor to detect the RIs of analytes range 1.33-1.41 within visible-near infra-red (IR) wavelength range<sup>8</sup>. H. Suzuki et al. reported a gold thin coated refractive index detection optical fiber SPR sensor. They have found the enhanced sensitivity 1557 nm/RIU in 1.333-1.3469 RI range<sup>14</sup>. Santos et al. investigated the gold (Au)/tantalum pentoxide ( $\text{Pa}_2\text{O}_5$ ) utilized D-type SPR sensor<sup>15</sup>. S. Shukla et al. theoretically studied the bilayer SPR sensor and found the highest sensitivity 3161 nm/RIU for 40 nm Gold (Au)/15 nm zinc oxide (ZnO) bilayer. And it capable to detect the 1.33-1.37 RI range sample<sup>77</sup>. In last years, many other D-shaped<sup>78</sup>, U-bent shaped<sup>79</sup>, and microstructure<sup>80</sup> fiber SPR sensors also reported for different applications. Based on this literature survey, single layer coated optical fiber sensors structures are very simple. The unique properties exhibited by noble metal nanowires have

paved the way for the development of advanced sensing platforms with exceptional capabilities. J. M. Renoirt et al. reported a silver (Ag) nanowires coating refractive index sensing optical fiber SPR sensor<sup>81</sup>. A bi-metallic nanowire grating utilized refractive index detection IR optical fiber SPR sensor was designed by the D. Feng et al. This sensor capable to detect the RI of the analyte range of 1.33-1.49 and achieved the highest sensitivity of 643.75 nm/RIU<sup>17</sup>. D. F. Santos et al. investigated an Au-wire-assisted D-type fiber SPR sensor. By employing the wavelength interrogation method, numerical analysis was conducted to evaluate the resolution and sensitivity for different RI of the analyte range 1.30 - 1.40. The sensor achieved the optimum sensitivity of 8437 nm/RIU<sup>53</sup>. H. Si et al. published a gold (Au) nanowires used RI sensing SPR fiber sensor with maximum sensitivity of 4400 nm/RIU<sup>82</sup>. Numerous metal oxide materials demonstrate plasmonic behavior, which is utilized in optical fiber SPR sensors. An indium tin oxide (ITO) thin film coated fiber SPR sensor was presented by R. K. Verma et al<sup>83</sup>. W. H. Tsai et al. proposed an Al-doped ZnO (AZO)/gold (Au) double layer utilized fiber optic SPR sensor<sup>84</sup>. Solid-core optical fiber sensors face limitations in detecting analytes with a refractive index higher than the refractive index of the fiber core, primarily due to the principle of total internal reflection. Hollow-core optical fiber-based SPR sensors can overcome the challenge of detecting analytes with high refractive indices. This is achieved by allowing liquid analytes to fill the hollow core of the fiber in these sensor configurations. N. Luan et al. submitted a silver (Ag) nanowire utilized hollow-fiber based SPR sensor for high RI detection range of 1.47-1.51<sup>85</sup>. A. K. Pathak et al. designed a metal nanowire used hollow-core fiber SPR sensor which have high sensitivity of 12400 nm/RIU<sup>56</sup>. The literature survey clearly demonstrates that optical fiber SPR sensors can be designed in diverse structural forms by utilizing various shapes of plasmonic materials. These sensors serve different purposes and find applications in a wide range of fields.

### 1.11 Motivation

In recent years, numerous research papers have been published focusing on the optical fiber sensing technique. The flexibility of the optical fiber structure and the ability to make geometric alterations, coupled with the unique properties of plasmonic materials, provide strong motivation for further research in this field. The combination of these factors offers exciting possibilities for advancements and innovations in optical fiber sensing. In the present era, sensors play a vital role in various fields such as chemical industries, environmental monitoring, biomedical and healthcare sectors, and food quality monitoring, among others. In these fields, there is a growing demand for real-time monitoring and highly responsive optical fiber sensors. This motivation drives us to simulate optical fiber sensors in the field of optical fiber sensing. my main focus and motivation in this research is to simulate an optical fiber-based sensor that exhibits the simple and flexible design, real-time and highly sensitive monitoring, and long range RI of analytes detection.

### 1.12 Thesis objective

The primary objective of the thesis is to “Design and simulation of surface plasmon resonance based optical fiber refractive index sensors” This primary objective has been divided into four sub-objectives, which are as follows:

- Design and simulation of metal-coated D-shaped refractive index detection optical fiber SPR sensor.
- Design and simulation of Single gold nanowire utilized refractive index SPR optical fiber sensor.
- Design and simulation of D-shaped Al-doped ZnO coated low refractive index detection optical fiber sensor

- Design and simulation of Hollow-core high refractive index sensing optical fiber SPR sensor.