Design & Analysis of Photonic Crystal Fiber Biosensor Using Surface Plasmon Resonance

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Declaration

This is to certify that the work entitled **Design & Analysis of Photonic Crystal Fiber Biosensor Using Surface Plasmon Resonance** is the outcome of the research carried out by us under the supervision of Dr. Mohammad Rakibul Islam, Professor, Department of Electrical and Electronic Engineering (EEE), Islamic University of Technology (IUT) Gazipur-1704, Bangladesh

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In our capacity as co-supervisor of the candidate's thesis, we certify that the above statements are true to the best of my knowledge.

Abstract

A perfectly circular lattice Photonic Crystal Fiber (PCF) based Surface Plasmon Resonance (SPR) sensor has been proposed in this thesis paper. The proposed sensor would be able to detect the unknown analytes by flowing through the metal surface or dripped on the outer surface of the metal layer. Photonic Crystal Fiber (PCF) based Surface Plasmon Resonance sensors have gained the popularity for detecting unknown analytes. Chemically stable active plasmonic material Gold (Au) and sensing layer are used outside the fiber structure to make a simple configuration. The investigation process has been carried out by using the finite element method (FEM) based commercial available software package COMSOL Multiphysics version 5.3.a.The proposed sensor shows maximum amplitude sensitivity of 1607 RIU^{-1} at refractive index 1.36. This PCF based sensor can sense the refractive indices ranges from 1.33-1.38. Furthermore, sensitivity of the sensor is investigated by varying the value of different parameters such as Au (Gold) layer thickness, Perfectly Matched Layer (PML) thickness and air-hole diameter. The proposed sensor can detect biological analytes because of its high sensitivity, improved sensing resolution and suitable linearity.

Acknowledgement

We are happy to disseminate profound gratefulness to the Allah for granting us the competency and the potency to finish the research effectively within the pre-set time.

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Chapter 1

Introduction

1.1 Background

Due to real time sensing and ultra –high refractive index sensitivity, Surface Plasmon Resonance (SPR) sensors have shown the much attention since last few decades [1]. A combined oscillation of electrons at metal-dielectric surface by hitting the metal field with light wave. This phenomenon is called Surface Plasmon Wave(SPW).The phenomenon SPR(Surface Plasmon Resonance) is the oscillation of conduction electrons at the interface between negative and positive permittivity simulated by incident light [2]. Generally the commercial prism coupled geometry is used for the SPR sensors. Prism is used to pass the light to the metal surface interface, whereas transverse magnetic (TM) or p-polarized light is induced in the metal or dielectric interface. The prism based SPR sensor is bulky and it limits the remote sensing capabilities. To overcome those problems, photonic crystal fiber based SPR sensor is introduced [3]. PCF is small in size. It has higher beam quality, scalability, efficiency and has design flexibility. Based on the applications, core-guided leaky-mode propagation can be controlled by using different types of PCF's structures such as hexagonal, square ,circle, octagonal, decagonal, hybrid, etc. Guiding can also be controlled by optimizing the structural parameter [4, 5]. PCF based SPR sensors work on the basis of evanescent field which is produced due to the light propagation through the core-cladding region. The evanescent tails of the surface plasmon light interact with the plasmonic surface. Therefore, the refractive index (RI) of the guided light will change. Due to change of the analyte refractive index (RI), the vicinity surface real part of the effective index of the surface plasmon polaritons (SPP) will change, as a result phase matching point or resonant wavelength also change. The particles or molecules are detected by measuring this resonant wavelength shifting. This is the basic working principle of the PCF SPR sensors [6, 7]. In 1993, first optical fiber based SPR sensor has been proposed by R.C. Jorgenson where, the fiber core was coated with the gold film by removing a section of the fiber cladding to exhibit the plasmonic response. Generally gold and silver metal are widely used as active plasmonic materials. Silver is a most conductive material. It's resonance peak is very sharp also it shows the higher detection accuracy compared to gold [8-13]. As an alternative plasmonic material, Gold is chemically stable even in aqueous environment. Moreover, it shows the larger wavelength shift at the resonant wavelength which helps for the easy detection and increase the accuracy to detect the unknown analyte accurately [14]. In spite of offering high sensitivity, it is a tough job to deposit the plasmonic material accurately in labelled area of the PCF in internal metal coated sensors. In contrast, in externally metal-coated sensors plasmonic material as well as the analyte is reserved outside the PCF surface which familiarizes fabrication feasibility and high sensitivity [15].

From last few decades, researchers have tried to develop distinct structures. They have found so many unique outcomes in order to gain maximum sensitivity with high confinement loss. They also to increase the performance of SPR sensors by increasing sensitivity. In this paper, we introduced a simple, regular PCF based SPR biosensor where the gold and sensing layer are placed outside the fiber structure which helps to reduce the design complexity and make the sensing process easier. The unknown analyte detection can be carried out by flowing the analyte. Our proposed sensor is simpler compared to the in terms of fabrication.

1.2 Motivation

Biosensor is a continuous monitoring sensor which is used in food analysis, study of biomolecules and their interaction, medical diagnosis, environment field monitoring, detection system for biochemical. Sensor sensitivities and others inherent parameters depend on refractive index and wavelength of incident light. Sensitivity actually measures the output changes extent or range for various input quantity. The main problem of those sensors is mainly the lower shift in wavelength which results in poor sensitivity. The problem can be solved by modifying the refracting index (RI) of the analytes used. Higher wavelength can be gained by optimizing the structural parameters such as wavelength, refractive index (RI), thickness and diameter of the layer etc. So we need to optimize the structural parameters to get higher sensitivity. Another thing we can do that is to use a chemically stable metal (Au) which shows higher wavelength shift. Detection accuracy depend on the sharpness of the resonance peak .We need to work for finding out simple design for fabrication with having higher sensitivity as possible as we can. The things needed to focus for thesis which are –simplest design, chemically stable metal using, wider range of RI, larger wavelength shifting for higher sensitivity.

1.3 Objectives

In this thesis work, a simple structured PCF based Surface Plasmon Resonance (SPR) bio-sensor is proposed. The major objectives of this thesis work are:

1. Conducting an in-depth literature review.
2. Use of gold as an external layer of the PCF structure which increases the stability and make fabrication more practical.
3. Gaining the wider range of Refractive Index(RI) for optimizing
4. Obtaining the dynamic detection
5. Investigation for higher wavelength shift
6. Investigating better sensitivity (amplitude sensitivity, wavelength sensitivity), higher resolution, accurate linearity by changing the performance parameter such as wavelength, RI, thickness of Gold layer and diameter of air holes etc.

1.4 Probable outcomes

1. A simple high sensitive PCF based sensor is designed for sensing purposes.

2. Chemically stable metal Gold is used as an external layer for proper fabrication.

3. A sensor with wide range refractive index can be possible.
4 .Enhancing the dynamic range.

5. Increasing the resolution by varying performance parameters.

6. A high sensitive PCF based sensor which is capable of detecting the unknown analytes.

7. A SPR senior with proper linear characteristics can be achieved.

1.5 Methodology

In this chapter, all numerical tools and methods described have properly used for making a simple high sensitive bio sensor. These methods as well as the numerical tools are needed for obtaining the probable outcomes and completing the objectives.

1.5.1 Finite Element Method

Finite Element method (FEM) is a numerical method for solving the problems of engineering and mathematical physics. The analytical solution of the mathematical problems generally require the solution to boundary value problems for partial differential equations. It formulates the problems results in a system of algebraic equations. The method approximates the unknown function over domain [16]. To solve the problem, it subdivides a large system into smaller, simple parts that are called finite elements. The simple equation that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses various methods from the calculus of variations to approximate a solution by minimizing associated error function. There are many types of FEM .They are:

1. AEM

2. GFEM

3. MFEM

4. hp-FEM

5. XFEM

6. SBFEM etc.

A GENERAL PROCEDURE FOR FINITE ELEMENT ANALYSIS:

1. Pre-processing – Define the geometric domain of the problem. – Define the element type(s) to be used. – Define the material properties of the elements. – Define the geometric properties of the elements (length, area, and the like). – Define the element connectivity's (mesh the model). – Define the physical constraints (boundary conditions). Define the loadings. Solution – computes the unknown values of the primary field variable(s) – computed values are then used by back substitution to compute additional, derived variables, such as reaction forces, element stresses, and heat flow.

2. Post-processing – Postprocessor software contains sophisticated routines used for sorting, printing, and plotting selected results from a finite element solution.

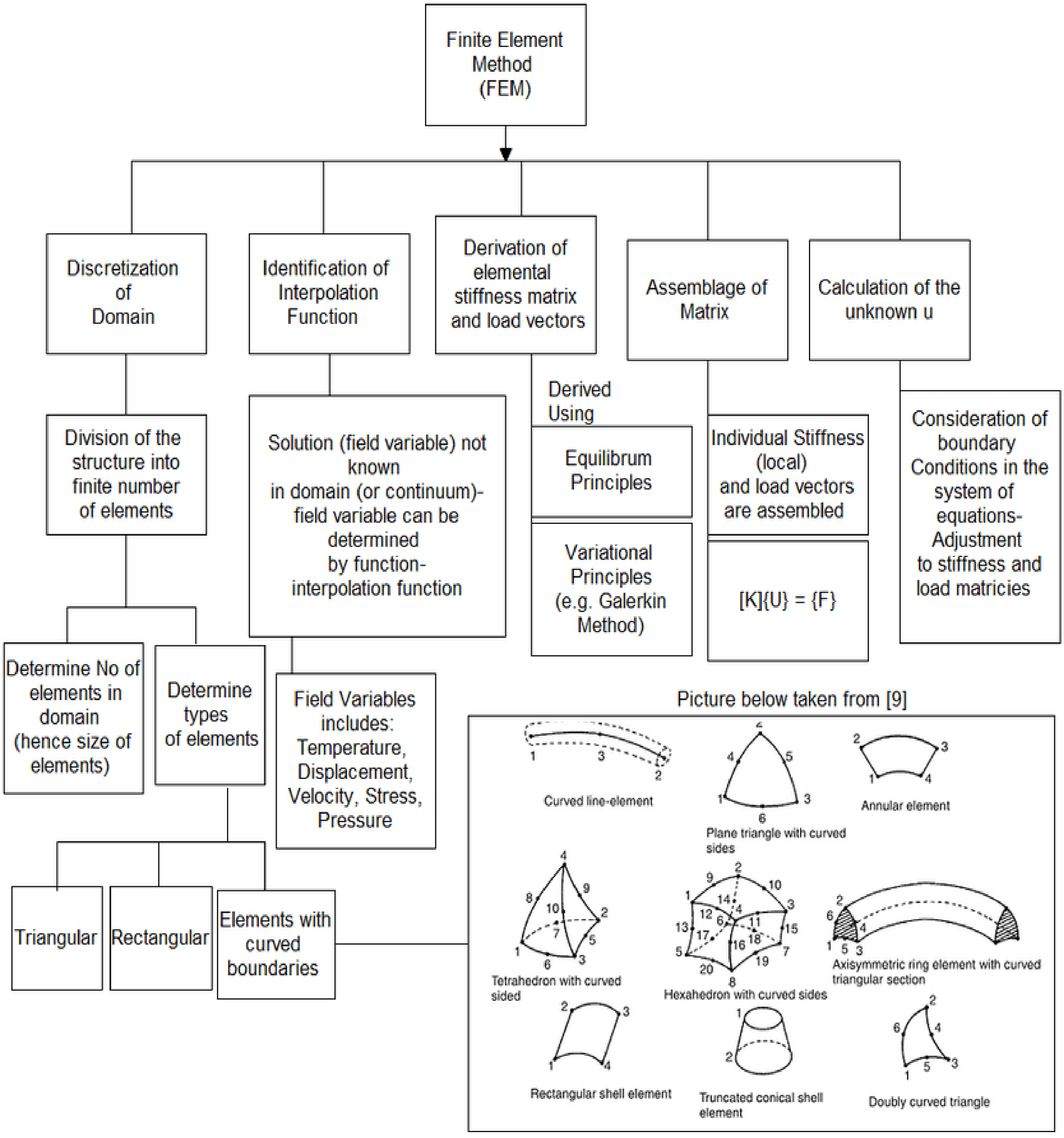


Figure 1.1: The Finite Element Idealization by a flow chart

1.5.2 Perfectly Matched Layer (PML)

A **Perfectly Matched Layer** (**PML**) is an artificial absorbing layer for wave equations, commonly used to truncate computational regions in numerical methods to simulate problems with open boundaries, especially in the FDTD and FE methods. The main property of a PML that distinguishes it from an ordinary absorbing material is that it is designed so that waves incident upon the PML from a non-PML medium do not reflect at the interface—this property allows the PML to strongly absorb outgoing waves from the interior of a computational region without reflecting them back into the interior.

PML was originally formulated by Berenger in 1994 for use with Maxwell equations, and since that time there have been several related reformulations of PML for both Maxwell's equations and for other wave-type equations, such as electrodynamics, the linearized Euler equations, Helmholtz equations, and poroelasticity. Berenger's original formulation is called a split-field PML, because it splits the electromagnetic fields into two unphysical fields in the PML region. A later formulation that has become more popular because of its simplicity and efficiency is called uniaxial PML or UPML in which the PML is described as an artificial anistropic absorbing material [17-19].

1.5.3 Numerical Methods and Sensor Designing

1.5.3.1 Effective Refractive Index

The refractive index can be seen as the factor by which the speed and the wavelength of the radiation are reduced with respect to their vacuum values: the speed of light in a medium is $v = c/n$, and similarly the wavelength in that medium is $\lambda = \lambda 0/n$, where $\lambda 0$ is the wavelength of that light in vacuum.

In this paper, we have varied the effective refractive index of layer for optimizing and obtained the maximum possible resolution and sensitivity.

1.5.3.2 Confinement Loss

Confinement losses are the losses arising from the leaky nature of the modes and the non-perfect structure of the PCF fiber. Then, depending on the wavelength, number of holes rings, and hole size, modes will be guided with a structure dependent loss. This loss Lc is acquired

$$Lc(\text{dB/cm}) = 8.686 * k0 * Im[neff] * 10000 \quad [1.1]$$

Where Im [η_{eff}] is the imaginary part, $k_0 = 2\pi/\lambda$. Using Maxwell's equations as an eigen value problem with the FEM, the complex RI of fundamental mode can be solved [20]. This loss depends on core size, Pitch and air-hole dimension, number of rings in the cladding etc. We have need to work for low loss high sensitive SPR sensor.

1.5.3.3 Wavelength Interrogation Method

Sensitivity of SPR sensor depends on maximum resonance wavelength shift. It can be measured using wavelength interrogation method. This method has many advantages over Amplitude detection method. It provides higher sensitivity, flexibility and mobility. Sensitivity here is defined as [21]

$$S\lambda(\text{nm/RIU}) = -\Delta\lambda peak / \Delta na \quad [1.2]$$

Where λpeak represents the peak wavelength shift for any variation in analyte RI. Δna is the difference between two consecutive RIs.

1.5.3.4 Amplitude Interrogation method

Amplitude sensitivity does not require wavelength interpolation and so it is simple and economic. Sensitivity here is expressed as [22].

S(1/RIU)= $-\{1 \div \alpha(\lambda,\eta)\}\{\partial\alpha(\lambda,\eta) \div (\partial\eta)\}$

Here, n is analyte RI and for this, $\alpha(\lambda, n)$ is the confinement loss. Again confinement loss difference is prescribed as $\delta\alpha(\lambda, n)$.

1.5.4 Software Used Thesis Work

There are 3 Software used in this thesis. They are as follow:

1. **Comsol Multiphysics**: Multiphysics software is built from the ground up to be multiphysics capable so that the user can easily combine models representing different physics phenomena in whichever way they wish. Sometimes this can be achieved simply by using built-in features of the software, but in other cases, the user will need to do a little bit of extra work. With this you can design Photonic Crystal Fiber easily by defining the sub-domains and boundary conditions with correct parameters and also you can solve the problems for both electric field and magnetic field. For designing the structure Comsol Multiphysics version 5.3.a is used.

2. **MATLAB**: Here MATLAB is mainly used for obtaining the curve of confinement loss, resolution curve, sensitivity curve based on amplitude and wavelength sensitivity

3. **Microsoft Excel:** It is used to store the collected data from Comsol software 5.3.a which are went to MATLAB later for getting the desired various curves described in previous section.

1.6 Thesis Information

The thesis comprises six chapters. These demonstrate the whole work to attain the objectives and probable outcomes which are described in previous sections

CHAPTER 1: Discusses background of PCF based SPR biosensors and objectives of this thesis. It also describes about the future expected outcomes and details methods related with this thesis work

CHAPTER 2: Based on the literature review of the prevailing work on PCF SPR sensors. It also narrates the possible future outcomes of the work.

CHAPTER 3: Consists of the explanation of the working principle of PCF and SPR. The application of SPR sensor is also included in this chapter.

CHAPTER 4: Consists of the structure, design of the proposed PCF based SPR sensor. The performance parameters are studied and results, graphs are also showed in this chapter.

CHAPTER 5: It is mainly the conclusion of the whole work. Limitations and some recommendations are also prescribed here.

1.7 Summary

The wordiness of the research has been attached in this chapter. The whole work's objectives, methodology, expected outcomes and whole possible analysis are briefly described here so that one can easily get the basic ideas and overview of the thesis work. It also reflects the goal and probable achievements of the thesis work.

The conciseness of the research has been provided in this chapter. In addition, the goals and purposes of the research have been stated which give an obvious idea on the whole research.

Chapter 2

Background and Literature Review

2.1 Background

Nowadays, there are various kinds of optical fiber sensors procurable on market at relatively low cost. These kinds of devices have become commercially interesting being integrated with practical detection and signal –processing electronics. Therefore, a huge volume of scientific literature has been produced on this topic during the last decades. Several laboratory prototypes have been constructed and characterized, paving the way for novel feasible measurement set-ups. It is well known that photonic crystal fibers (PCFs), thanks to their micro structured section have allowed the improvement of optical amplification and lasing, beam quality, high power delivering, extreme core confinement such as large mode area, nonlinear.

The comprehensible facts of SPR were first explained by Wood in 1902 [22, 23]. He based sensors are used mainly to decrease the technical cost and the size of sensor devices noticed a shape of "exceptional" divergent in the mirrored light. In 1983, Liedberg et al firstly exhibited the usance of SPR based sensor to monitor the biomolecular interaction [24]. They were skilled to comprehend the straight and instantaneous detection of the bio-molecular interaction by applying the SPR sensing method. SPR has found theoretically by Ritchie et al. in the 1950s at first. Liedberg et al. in 1983 first introduced about SPR based on prism coupling. Generally, the commercial prism couple geometry is used for the SPR sensors. Prism used to pass the light to the metal surface interface whereas transverse magnetic or p-polarized light is induced in the metal or dielectric interface. This occurs when the light is incident on the metal surface and the free electrons of the metal absorb the light and generate Surface Plasmon wave (SPW). For activating surface plasmon, the prism is generally used. Prism based SPR sensing device has some limitations such as; it provides a bulky size device with various kinds of mechanical and optical parts, in remote sensing application it is not suitable to use. The optical fiber is used instead of the prism to minimize the allusive limitation. SPR.

In 1993, optical fiber based on the SPR sensor was introduced by R.C. Jorgenson first, where the gold film was used in the fiber core to reveal the plasmon response PCF has gained its importance because it has different appealing characteristics e.g. controllable birefringence, high confinement and single mode propagation. Utilizing these characteristics, an evanescent field can be manipulated easily. The effective sensitive performance of the fiber is controlled by the evanescent field. The presence of plasmonic devices, the high surface to volume ratio, broadband optical and plasmonic properties make it suitable aspirant to be used as sensor and as a functional coating material [6-9, 13-15].

SPR sensors nowadays give high sensitivity rather than fiber based sensors. It also gives a low resonance peak than fiber based sensors .The PCF based sensors also provide a flexible design. Most SPR sensors based PCF works used gold or silver. Here, in this raised structure we consider gold layer because gold is chemically stable and shows larger shifts in resonance wavelengths.

In order to improve the performance of the SPR sensors, the researchers have tried to construct unique structure from last few decades. They have carried out maximum sensitivity with high confinement loss by their innovative works. They have also successfully able to increase the performance of SPR sensors.

2.2 Literature Review

Various designs of plasmonic PCF structures has been proposed to achieve desirable characteristics, e.g. sensitivity, detection range, stability, miniaturization etc. for a wide range of applications including measurement of refractive index(RI), dual or multi-analyte sensing, temp sensing , polarization devices and couplers. In this section, the plasmonic PCF designs are categorized and reviewed based on their target applications. Gold and silver are two commonly used metals for SPR sensors. Gold or Silver coated SPR sensors are investigated in visible wavelengths where the plasma frequencies of both materials are located. Specifically, Gold is favoured because of its availability, chemical stability and strong SPR signal which results in good detection sensitivity. On the other hand, silver has a sharp resonance peak which offers better performance in terms of detection sensitivity.

The phase matching condition of the plasmonic and fiber modes is ultrasensitive to refractive index (RI). This property has generated immense interest in the exploration of plasmonic fiber designs for RI sensing applications. High RI sensitivity is a key enabler to develop bio sensing devices. The key designs were selected based on authors' perspectives with the best effort to represent plasmonic PCF designs of the same class. Phase matching conditions in plasmonic fiber sensors are assessed at the intersections of the effective mode index of the core mode and the surface plasmons, i.e. at phase matching wavelength, the real part of the effective mode index of the fiber waveguide and the surface plasmons are equal. An important parameter, i.e. the confinement loss which is related to the imaginary part of the effective mode index of the fiber waveguide mode, is usually used for characterization of the plasmonic sensor, especially for amplitude interrogation and wavelength interrogation methods.

PCF SPR sensor with bigger microfluidic channels was proposed. This PCF shows wavelength sensitivity of 2000 nm/RIU. It appears amplitude sensitivity of 300 RIU^{-1} at refractive indices from 1.33 to 1.39 [25]. The paper [25] exhibits wavelength sensitivity 4000 nm/RIU and amplitude sensitivity 478 RIU^{-1}. These are realized with resolution 2.5×10^{-5} and 2.1×10^{-5} RIU respectively at refractive indices range of 1.33-1.37. In [26], wavelength sensitivity 4000 nm/RIU with amplitude sensitivity 320 RIU^{-1} are attained with the sensor resolutions 2.5×10^{-5} and 3.125×10^{-5} RIU at sensing range 1.34 to 1.36. To date, numerous PCF SPR sensors have been reported. From the above study, various kinds of sensors of different wavelength and amplitude sensitivity are observed. All have diverse structures. Problems statements are some sensors have low sensitivity and some offered difficult designs. High sensitivity and fine resolution are desirable for a good sensor. On the other hand, the scope of practical fabrication is essential for a design. Some proposed design put plasmonic material in internal air holes which is tough for fabrication. Previous study showed the scope for spiral fabrication as well as external covering surface with material. Low linearity is also deficient for a sensor.

This paper demonstrate a simple designed PCF to gain high sensitivity and resolution. A layer of gold is used as plasmonic material in the external surface of the PCF structure. It is done to simplify detection mechanism and fabrication process. There are so many performance parameters of sensor like as wavelength sensitivity, amplitude sensitivity, sensor resolution and linearity are mainly used. To acquire the optimal sensing performance, design parameters are studied here which includes pitch, air hole diameter and gold layer thickness

Chapter 3

Photonic Crystal Fiber (PCF) & Surface Plasmon Resonance (SPR)

3.1 Photonic Crystal Fiber (PCF)

3.1.1 History of PCF

Photonic crystal fibers (PCFs), also known as micro structured optical fibers, or holey fibers, contain axially aligned air holes which can be arranged periodically or non-periodically in the cladding region centred on a solid or hollow core. These fibers provide unique features and flexibilities not attainable in conventional optical fibers since its discovery in 1996, the past two decades have witnessed substantial development of PCF technology for sensing, communication and medical applications [27, 28]. Particularly for sensing applications, PCFs have attracted significant attention in light of the ever increasing demand for high performance sensing devices [29]. The incorporation of plasmonic structures into PCFs seems a natural move of plasmonic fiber optic technology, as PCFs allow unparalleled flexible control of wave guiding properties through engineering the holey structures. As a desirable platform for plasmonic structures, PCFs enable and enhance many application opportunities in terms of performance and versatility. In 2000, eminently birefringent PCF was offered and super continuum construction having PCF was familiarized for the first time [30]. Formation of a Bragg fiber was made firstly in 2001. In that year, PCF laser with twofold cladding was delivered as well for the first time [31]. In the year 2002, PCF with ultra-flattened dispersion was commenced. Large power transmission, Low-loss alterations among PCFs and Photonic band gaps at 1% index contrast were promoted in 2005.

The potential impact of plasmonic PCFs has resulted in growing effort in developing new device features for all kinds of applications. There exists a need to have a comprehensive review on using PCFs as a platform for both SPR and LSPR structures for a wider spectrum of applications including temperature sensors and polarization splitters etc. In this thesis work, we first summarize the current state-of-the-art achievements in the design, fabrication and application experiments of plasmonic PCFs. We then identify important research directions for the research community. This review begins with an introduction on the operating principles of plasmonic fibers, then followed by an overview on the progress in fabrication techniques and experimental studies. In the second half of this review, we present a summary on various plasmonic PCF structures, which are classified based on their respective applications with benchmarking, and a discussion on their opportunities and challenges

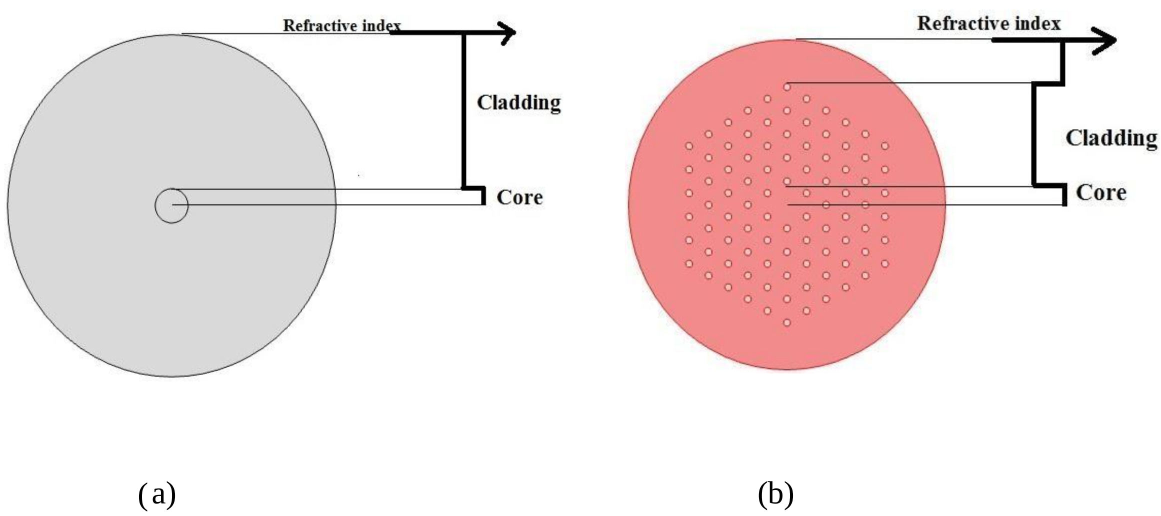


Figure 3.1: (a) Conventional step-index fiber (b) Photonic crystal fiber

3.1.2 Light Guiding Mechanism of PCF

Photonic crystal fiber is an independent technology. It has the form of a finite, two-dimensional photonic crystal usually with a defect in the center. There are several variations of photonic crystal fibers that are used in applications. Photonic crystal fibers are classified into solid band hollow core types. Under these two types, there are many different types of photonic crystal fibers. The lattice symmetry, pitch, and holes size can be changed to suit the design of a specific fiber type. The solid core class of fibers has a high-index solid core with a lower effective index surrounding medium. The hollow core fibers have a lower index than the surrounding medium, and confinement to the centre core hole is made possible by scattering and interference, combining to form an evanescent field in the cladding region. [30-31]

Total Internal Reflection (TIR) is the most basic and well known principle of guiding light in traditional fibers. The most of the TIR crystal fibers have solid core enclosed by a covering with a regular periodic array of air holes [28]. Photonic crystal fibres (PCFs) are a special class of optical fibres characterized by a periodical arrangement of microcapillaries that form the fibre's cladding around a solid or hollow defect core [32]. The engineering of the PCF geometry combined with an ample selection of available materials for their fabrication provides extensive degrees of freedom for the tailoring of their optical properties, such as modal area, chromatic dispersion, nonlinearity and birefringence. Compared to their conventional counterparts, PCFs can exhibit unprecedented performance in a broad range of applications which span from large-mode-area endlessly single-mode fibres, dispersion compensation, single-polarization and high-birefringence guidance, and nonlinear applications.

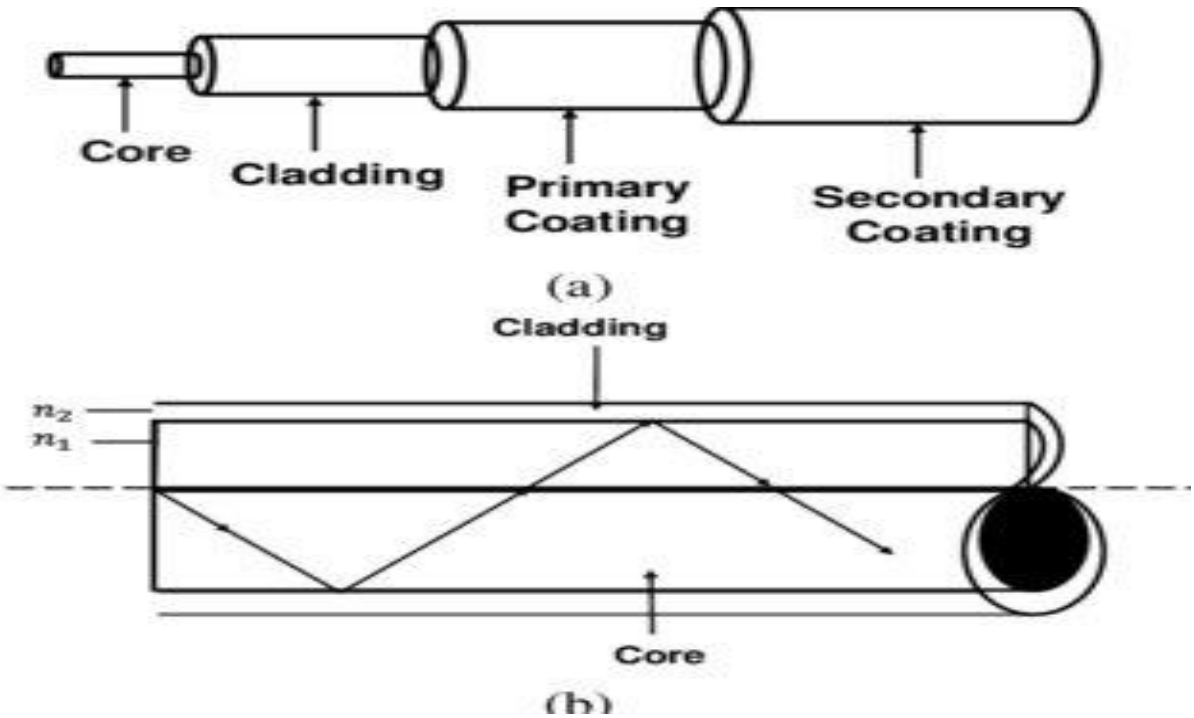


Figure 3.2: Fiber passing Light with TIR

3.2 Surface Plasmon Resonance sensor

3.2.1 SPR Theory

Surface Plasmon Resonance (SPR) is the resonant oscillation of conduction electrons at the interface between negative and positive permittivity material stimulated by incident light. SPR is the basis of many standard tools for measuring adsorption of material onto planar metal (typically gold or silver) surfaces or onto the surface of metal nanoparticles. It is the fundamental principle behind many colour-based biosensor applications, different lab-on-a-chip sensors and diatom photosynthesis.

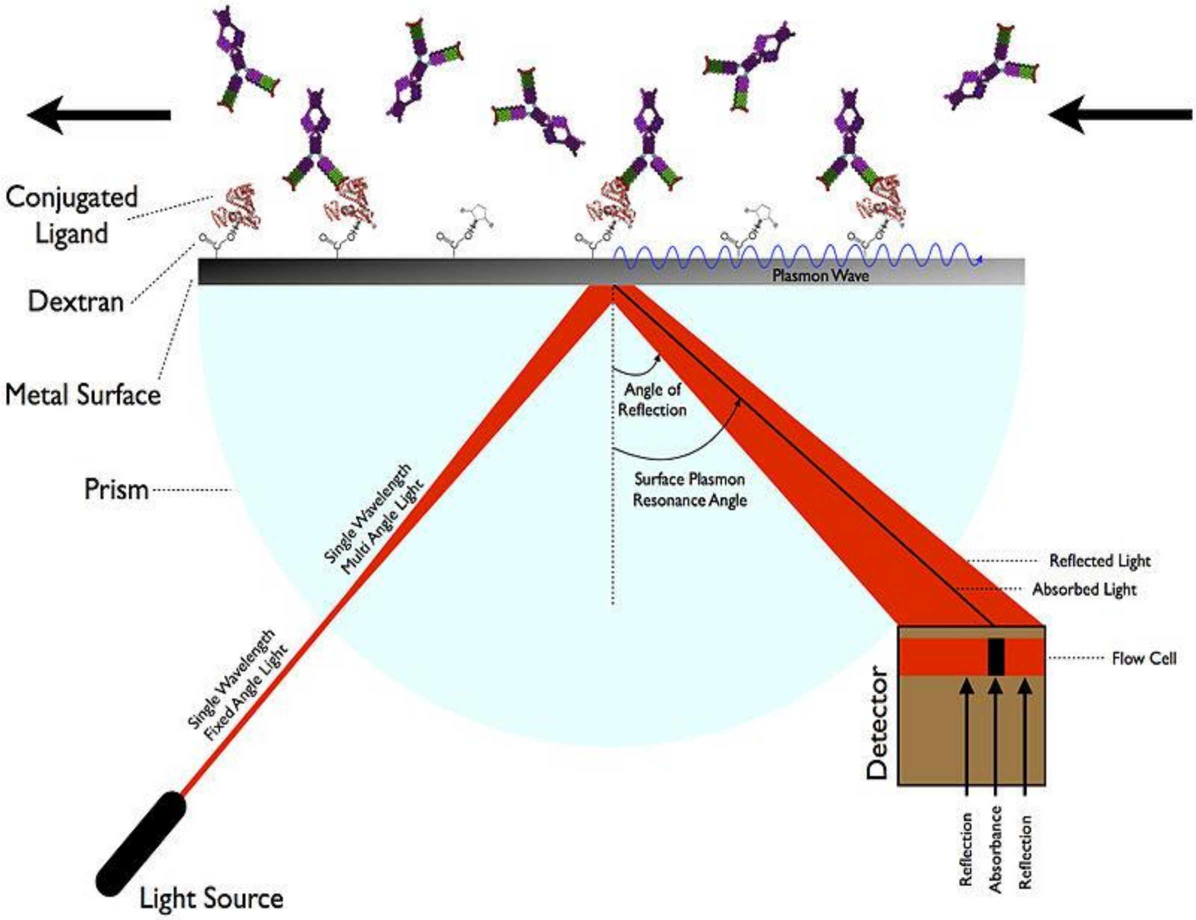


Figure 3.3: SPR Configuration.

3.2.2 SPR Explanation

The Surface Plasmon Polariton is a non-radiative electromagnetic surface wave that propagates in a direction parallel to the negative permittivity/dielectric material interface. Since the wave is on the boundary of the conductor and the external medium (air, water or vacuum for example), these oscillations are very sensitive to any change of this boundary, such as the adsorption of molecules to the conducting surface. [33]

To describe the existence and properties of Surface Plasmon Polaritons, one can choose from various models (quantum theory, Drude model, etc.). The simplest way to approach the problem is to treat each material as a homogeneous continuum, described by a frequency-dependent relative permittivity between the external medium and the surface. This quantity, hereafter referred to as the materials' "dielectric function", is the complex permittivity. In order for the terms that describe the electronic surface plasmon to exist, the real part of the dielectric constant of the conductor must be negative and its magnitude must be greater than that of the dielectric. This condition is met in the infrared-visible wavelength region for air/metal and water/metal interfaces (where the real dielectric constant of a metal is negative and that of air or water is positive).

LSPRs (localized Surface Plasmon Resonances) are collective electron charge oscillations in metallic nanoparticles that are excited by light. They exhibit enhanced near-field amplitude at the resonance wavelength. This field is highly localized at the nanoparticle and decays rapidly away from the nanoparticle/dielectric interface into the dielectric background, though far-field scattering by the particle is also enhanced by the resonance. Light intensity enhancement is a very important aspect of LSPRs and localization means the LSPR has very high spatial resolution (subwavelength), limited only by the size of nanoparticles. Because of the enhanced field amplitude, effects that depend on the amplitude such as magneto-optical effect are also enhanced by LSPRs. [34]

3.2.3 SPR Excitation and Emission

In order to excite surface plasmons in a resonant manner, one can use electron bombardment or incident light beam (visible and infrared are typical). The incoming beam has to match its momentum to that of the plasmon [32-33]. In the case of p-polarized light (polarization occurs parallel to the plane of incidence), this is possible by passing the light through a block of glass to increase the wavenumber (and the momentum), and achieve the resonance at a given wavelength and angle. S-polarized light (polarization occurs perpendicular to the plane of incidence) cannot excite electronic surface plasmons. Electronic and magnetic surface plasmons obey the following dispersion relation:

$$k(\omega) = \frac{\sqrt{(\in 1\mu 1)(\mu 2 \in 2)}}{\sqrt{(\in 1 + \mu 1)(\in 2 + \mu 2)}}$$

Where k (ω) is the wave vector, $\in$ is the relative permittivity, and μ is the relative permeability of the material (1: the glass block, 2: the metal film), while ω is angular frequency and w is the speed of light in a vacuum.

Typical metals that support surface plasmons are silver and gold, but metals such as copper, titanium or chromium have also been used.

When using light to excite SP waves, there are two configurations which are well known. In the Otto setup, the light illuminates the wall of a glass block, typically a prism, and is totally internally reflected. A thin metal film (for example gold) is positioned close enough to the prism wall so that an evanescent field can interact with the plasma waves on the surface and hence excite the plasmons.

In the Kretschmann configuration, the metal film is evaporated onto the glass block. The light again illuminates the glass block, and an evanescent wave penetrates through the metal film. The plasmons are excited at the outer side of the film. This configuration is used in most practical applications.

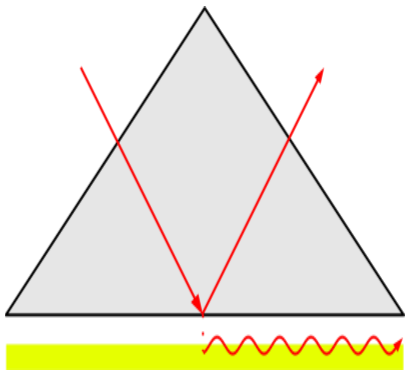


Figure 3.4: Otto Configuration.

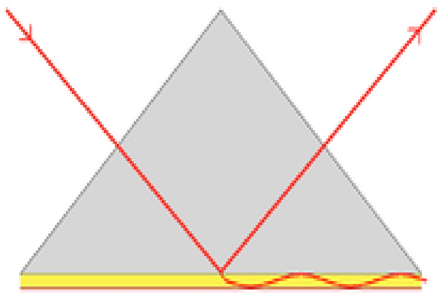


Figure 3.5: Kretschmann Configuration.

SPR Emission

When the Surface Plasmon Wave interacts with a local particle or irregularity, such as a rough surface, part of the energy can be re-emitted as light. This emitted light can be detected behind the metal film from various directions [34-35].

3.2.4 SPR Applications

Surface Plasmons have been used to enhance the surface sensitivity of several spectroscopic measurements including fluorescence, Raman scattering, and second harmonic generation. However, in the simplest form, SPR reflectivity measurements can be used to detect molecular adsorption, such as polymers, DNA or proteins, etc. Technically, it is common to measure the angle of minimum reflection (angle of maximum absorption). This angle changes in the order of 0.1° during thin (about nm thickness) film adsorption. (See also the Examples.) In other cases the changes in the absorption wavelength is followed [12-13] .The mechanism of detection is based on that the adsorbing molecules cause changes in the local index of refraction, changing the resonance conditions of the Surface Plasmon Waves. The same principle is exploited in the recently developed competitive platform based on loss-less dielectric multilayers (DBR), supporting surface electromagnetic waves with sharper resonances (Bloch surface waves) [18-19].

If the surface is patterned with different biopolymers, using adequate optics and imaging sensors (i.e. a camera), the technique can be extended to Surface Plasmon Resonance imaging (SPRI). This method provides a high contrast of the images based on the adsorbed amount of molecules, somewhat similar to Brewster angle microscopy (this latter is most commonly used together with a Langmuir–Blodgett trough).

For nanoparticles, localized Surface Plasmon oscillations can give rise to the intense colours of suspensions or sols containing the nanoparticles. Nanoparticles or nanowires of noble metals exhibit strong absorption bands in the ultraviolet-visible light regime that are not present in the bulk metal. This extraordinary absorption increase has been exploited to increase light absorption in photovoltaic cells by depositing metal nanoparticles on the cell surface. The energy (colour) of this absorption differs when the light is polarized along or perpendicular to the nanowire. Shifts in this resonance due to changes in the local index of refraction upon adsorption to the nanoparticles can also be used to detect biopolymers such as DNA or proteins. Related complementary techniques include Plasmon Waveguide Resonance, QCM, extraordinary optical transmission, and dual polarization interferometry.

3.2.5 SPR Operation

Surface Plasmon (SP) is the movement of many electrons at metal-dielectric interface. Surface Plasmon Resonance (SPR) is the propagation of Surface Plasmon Wave (SPW) along this interface. It occurs if the light photons' frequency equivalents the usual frequency of surface electrons. The electrons oscillation is induced by the incident light.

Surface Plasmon Resonance (SPR) is a physical process that can occur when plane-polarized light hits a thin metal film under total internal reflection conditions.

When a light beam hits a half circular prism, the light is bent towards the plane of interface, when it is passing from a denser medium to a less dense one. Changing the incidence angle (Θ) changes the out-coming light until it reaches a critical angle. At this point, all the incoming light reflects within the circular prism. This is called total internal reflection (TIR) [35-37].

Although no light is coming out of the prism in TIR, the electrical field of the photons extends about a quarter of a wavelength beyond the reflecting surface. Now the prism is coated with a thin film of a noble metal on the reflection site. In most cases, gold is used because it gives a SPR signal at convenient combinations of reflectance angle and wavelength. In addition, gold is chemically inert to solutions and solutes typically used in biochemical contexts. When the electrical field energy of the photon is just right, it can interact with the free electron constellations in the gold surface. These are the outer shell and conduction-band electrons. The incident light photons are absorbed and the energy is transferred to the electrons, which convert into surface plasmons.

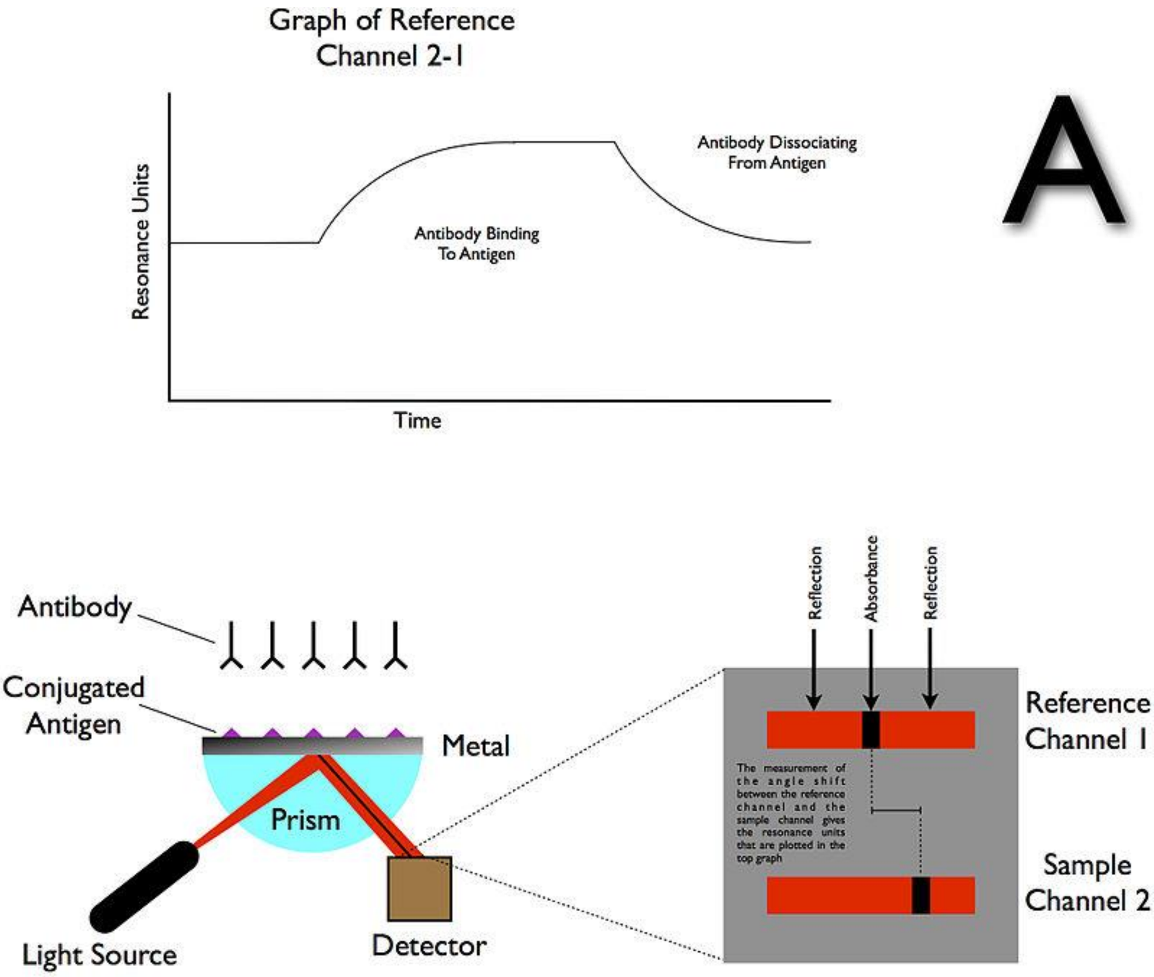


Figure 3.6: SPR Operation A

Photon and electron behaviour can only be described when they have both wave and particle properties. In accordance with the quantum theory, a plasmon is the particle name of the electron density wave. Therefore, when in a TIR situation the quantum energy of the photons is right, the photons convert to plasmons leaving a 'gap' in the reflected light intensity.

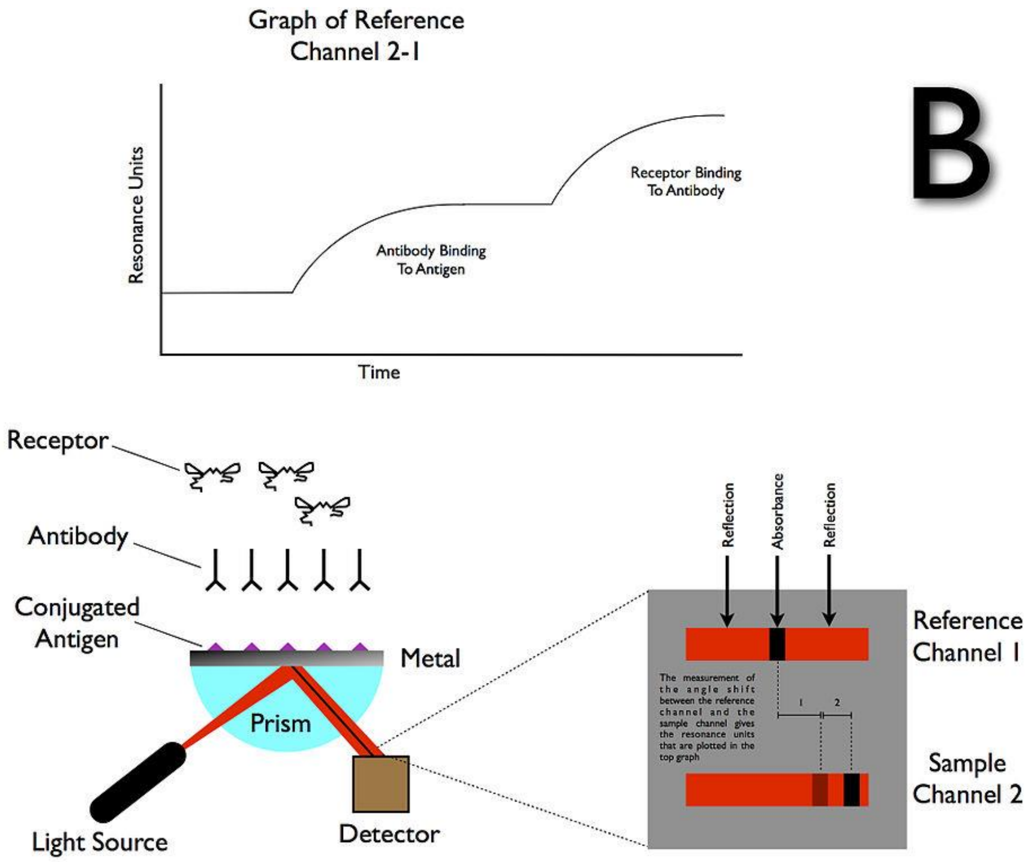


Figure 3.7: SPR Operation B

3.2.6 Fiber Optic Sensor

Light will propagate through a multimode optical fibre only if it enters the fibre at certain discrete angles. Each of these angles roughly corresponds to a different mode, or route of travel. Although modes are technically more of an energy distribution in the fibre, they can be thought of as different angles of total internal reflection as the light bounces back and forth along the fibre. Low-order modes enter the fibre core at a shallow angle, and therefore bounce back and forth slowly. The energy tends to be distributed primarily in the fibre core. Higher-order modes, on the other hand, enter at a steep angle and therefore bounce back and forth very rapidly. Their energy spreads more into the cladding, and due to the evanescent wave, beyond the boundary of the waveguide itself.

How, then, is SPR sensing achieved with only a limited number of entry angles? Rather than sweeping through a range of coupling angles, as with the Kretschmann prism, the fibre allows us to sweep through a number of coupling wavelengths. These wavelengths can be processed simultaneously by using a broadband, multi-wavelength source such as white light. By measuring the intensity of each wavelength leaving the fibre, a spectrophotometer can determine which wavelength coupled with the surface plasmon and consequently how much analyte is present. The fibre optic SPR sensor is constructed using a large diameter – usually 400 nm – multimode fibre. A certain length of the fibre is completely stripped of its cladding and a surface plasmon metal such as silver is deposited in its place. This length depends on the diameter of the fibre and determines the number of reflections occurring at the surface plasmon metal interface. If the length is too short, insufficient coupling will occur. If the length is too long, coupling will be very strong and the minimum coupling intensity will be difficult to determine.

Fibre optic waveguides have a number of advantages over the bulkier prism-based sensors. Primarily, they are inexpensive and can easily be used to make disposable sensors for medical or otherwise sterile tasks. Fibres are also very small and have no moving parts, giving them a much broader range than Kretschmann sensors and make a multiple sensor array a possibility.

3.2.7 G.C Sensor

The use of grating couplers (GC) for sensors was first introduced in 1983.The GC system makes use of the physics of a diffraction grating. For GC the sinusoidal grating is the optimal grating and the angle at which light couples into the waveguide depends on the biomolecules on the outside of the grating. The period (top-to-top) and amplitude (top-to-trough) of the grating will determine the wavelength of resonance. The grating replaces the need for a glass prism in traditional SPR. The grating is covered with gold. The light source illuminates the surface of the chip and the reflected light is captured by a CCD camera. By varying the incidence angle and measuring the reflected light intensity, a binding curve is created.

There are two common optical configurations for GC sensors: input and output grating couplers. An input grating coupler needs a light source to be shone through the substrate onto the GC. The sample affects the coupling angle, and a detector on the end of the waveguide senses the presence of light. On the other hand, an output grating coupler uses a pre-coupled light source. When the light reaches the GC, it is uncoupled at an angle dependent on the n_{eff}. The detector, which is not attached to the GC, observes this reflection.

3.2.8 Optical Waveguide Sensor

The optical waveguide systems have some attractive features. For example, they offer a simple way to control the optical path, and they are small and rugged. By varying the angle of incidence of the light, a light wave is guided by the waveguide. On entering the region with a grating (2400 lines/mm) and a thin metal overlay, it evanescently penetrates through the metal layer. At the end of the waveguide, the out-coming light is detected by photodiodes. An algorithm is used to model the adsorbed material linearly to surface concentrations.

3.2.9. Traditional SPR Vs Multi-parametric SPR

Traditional SPR uses the SPR dip minimum to determine the dip position as function of time. The dip position is presented in a sensor gram. This set-up provides information about the kinetics (k_a, k_d, K_D) and binding level (Rmax). Traditional SPR is widely used.

Multi-parametric SPR determines the SPR dip minimum / position but in addition, records the dip slopes, dip intensity and the surrounding SPR signal [15]. This enables multi-parametric SPR to resolve bulk-refractive index differences without a reference channel (inline referencing). This system tolerates up to 5% DMSO and running DMSO calibration is therefore not necessary.

By using a second wavelength layer thickness (Ångström resolution) and RI changes can be detected. Traditional SPR works with thickness up to 150 nm, MP-SPR can work with layers up to several microns thick, allowing work with living cells amongst others. In addition, MP-SPR is suitable to measure the layer properties (refractive index, thickness, density, extension coefficient, surface coverage, swelling, optical dispersion) of the sample.

In the Multi-parametric SPR figure several points of the SPR curve are highlighted:

1. Peak minimum position is the most used parameter in SPR
2. Intensity of SPR peak minimum depends on the sensor material and the media. Unlike others, MP-SPR is able to measure in liquid as well as in gas, on metals, metal oxides and hydrogels.
3. Total Internal Reflection (TIR) value is dependent on the bulk properties around the sensor and it is utilized for dn/dc calculation (inline bulk effect).

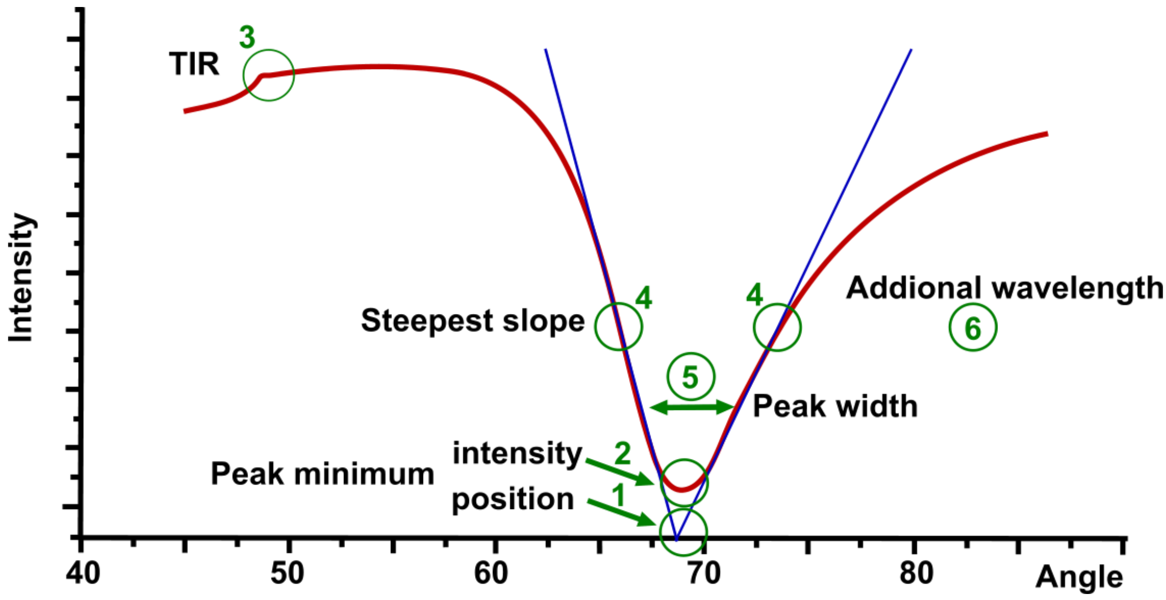


Figure 3.8: Multi-parametric SPR

4. Steepest falling and raising slope shows the most sensitive measurement area for the fast fixed angle measurements.
5. SPR peak-width at 3 different levels defines the shape of the SPR peak. It contains information on light absorption by the binding molecules and therefore, enables characterization of absorbing coatings and samples.
6. Another wavelength pair can be used for all measurements. This resolves layer thickness and RI.

3.3 Evanescent Wave

In TIR, the reflected photons create an electric field on the opposite site of the interface. The plasmons create a comparable field that extends into the medium on either side of the film. This field is called the evanescent wave because the amplitude of the wave decreases exponentially with increasing distance from the interface surface, decaying over a distance of about one light wavelength. The depth of the evanescent wave which is useful for measurements is within ~300 nm of the sensor surface. The wavelength of the evanescent field wave is the same as that of the incident light. The energy of the evanescent wave is dissipated by heat. Equations that describe how electric fields travel through a medium include a term for the properties of the medium. For light, this term is the refractive index. The light is seen as refracted because the photons have a different velocity in different media [38-39].

In the same way, the velocity (and therefore the momentum) of the plasmons is changed when the composition of the medium changes. Because of the change in momentum, the angle of incident light at which the resonance occurs.

3.4 Momentum Resonance

Like all conversions, the photon to plasmon transformation must conserve both momentum and energy in the process. Plasmons have a characteristic momentum defined by factors that include the nature of the conducting film and the properties of the medium on either side of the film. Resonance occurs when the momentum of incoming light is equal to the momentum of the plasmons (momentum resonance).

The momentum of the photons and plasmons can be described by a vector function with both magnitude and direction. The relative magnitude of the components changes when the angle or wavelength of the incident light changes. However, as plasmons are confined to the plane of the gold film, for SPR it is only the vector component parallel to the surface that matters. Thus, the energy and the angle of incident light must match to create surface plasmon resonance.

3.5 Data Interpretation

The most common data interpretation is based on the Fresnel formulas, which treat the formed thin films as infinite, continuous dielectric layers. This interpretation may result in multiple possible refractive index and thickness values. However, usually only one solution is within the reasonable data range. In Multi-Parametric Surface Plasmon Resonance, two SPR curves are acquired by scanning a range of angles at two different wavelengths, which results in a unique solution for both thickness and refractive index. Metal particle plasmons are usually modeled using the Mie scattering theory.

In many cases no detailed models are applied, but the sensors are calibrated for the specific application, and used with interpolation within the calibration curve.

3.6 Surface Plasmon polaritons (SPPs)

Surface Plasmon Polaritons (SPPs) are electromagnetic waves that travel along a metal–dielectric or metal–air interface, practically in the infrared or visible-frequency. The term "Surface Plasmon Polariton" explains that the wave involves both charge motion in the metal ("surface plasmon") and electromagnetic waves in the air or dielectric ("polariton").

They are a type of surface wave, guided along the interface in much the same way that light can be guided by an optical fiber. SPPs are shorter in wavelength than the incident light (photons). Hence, SPPs can have tighter spatial confinement and higher_local field intensity. Perpendicular to the interface, they have subwavelength-scale confinement. An SPP will propagate along the interface until its energy is lost either to absorption in the metal or scattering into other directions (such as into free space).

Application of SPPs enables subwavelength optics in microscopy and lithography beyond the diffraction limit. It also enables the first steady-state micro-mechanical measurement of a fundamental property of light itself: the momentum of a photon in a dielectric medium. Other applications are photonic data storage, light generation, and bio-photonics.

3.7 Surface Plasmon polaritons (SPPs) Excitation

SPPs can be excited by both electrons and photons. Excitation by electrons is created by firing electrons into the bulk of a metal. As the electrons scatter, energy is transferred into the bulk plasma. The component of the scattering vector parallel to the surface results in the formation of a surface plasmon polariton [36-39].

For a photon to excite an SPP, both must have the same frequency and momentum. However, for a given frequency, a free-space photon has *more* momentum than an SPP because the two have different dispersion relations (see below). This momentum mismatch is the reason that a free-space photon from air cannot couple directly to an SPP. For the same reason, an SPP on a smooth metal surface *cannot* emit energy as a free-space photon into the dielectric (if the dielectric is uniform). This incompatibility is analogous to the lack of transmission that occurs during total internal reflection.

Nevertheless, coupling of photons into SPPs can be achieved using a coupling medium such as a prism or grating to match the photon and SPP wave vectors (and thus match their momenta). A prism can be positioned against a thin metal film in the Kretschmann configuration or very close to a metal surface in the Otto configuration. A grating coupler matches the wave vectors by increasing the parallel wave vector component by an amount related to the grating period. This method, while less frequently utilized, is critical to the theoretical understanding of the effect of surface roughness. Moreover, simple isolated surface defects such as a groove, a slit or a corrugation on an otherwise planar surface provides a mechanism by which free-space radiation and SPPs can exchange energy and hence couple.

3.8 Summary

In this chapter, PCF, SPR, SPPs are described in details**.** PCF based SPR sensors are developing in sensitivity and capacity day by day. There are various kinds of optical fiber sensors procurable on market at relatively low cost. These kinds of devices have become commercially interesting being integrated with practical detection and signal – processing electronics. Therefore, a huge volume of scientific literature has been produced on this topic during the last decades. Several laboratory prototypes have been constructed and characterized, paving the way for novel feasible measurement set-ups. . Plasmonic fiber optic sensors imbibe the phenomenon of Surface Plasmon Resonance (SPR) that can occur on the dielectric-metal interface of a thin film metal when the guided propagation mode couples with Surface Plasmon Polariton (SPP) mode under phase-matching conditions. In recent literature, SPR sensors have been designed and fabricated for measurement of refractive index of liquids, temperature, magnetic field, biomolecules concentration for applications such as bio-sensing, environmental monitoring and medical diagnostics.

Chapter 4

Proposed Structural Design and Simulation

4.1 Introduction

The sketch of PCF can be exclusive like hexagonal, octagonal, spiral, D shaped for more than a few purposes.

For acquiring the favoured result a most beneficial layout is observed out. In this work circular PCF is proposed. COMSOL 4.2 software program is used here for the plan and simulation purpose. Using the FEM, guiding estates of the PCF are evaluated. PML boundary circumstances used. In this chapter, proposed format is defined elaborately. PCF primarily based sensor's sensing houses are also explored here by means of varying PCF parameters. All the effects are discussed in details in this chapter.

4.2 Sensor design

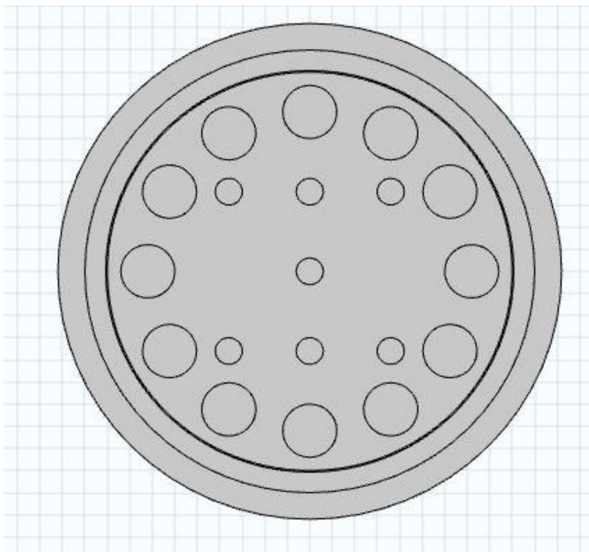


Figure 4.1: The X-section view of the proposed design

It shows the X-section view of the circular PCF design with larger air hole ring. Identical circular arm's air holes have consecutive angular shift (θ) of 30 degree.

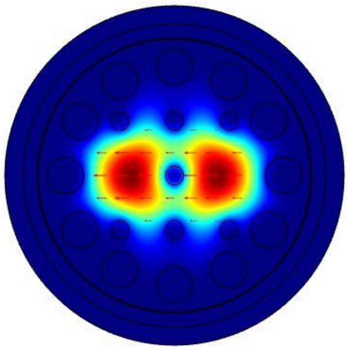
Outer surface is 35 nm gold layer coated (tg). Inside the circular air holes, there was made a square shape with smaller air holes .Two horizontal air holes of the square shaped ring are eliminated so that contact of transitory field with the sensing layer is increased. It was done for getting better confinement inside the core. Structure of the proposed design is constructed with fused silica and all the air holes are empty.

Using Drude- Lorentz model, the permittivity of gold cloth can be received [4].

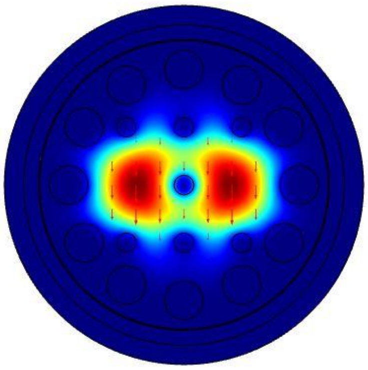
$$\varepsilon_{Au} = \varepsilon_{\infty} - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\varepsilon\,\Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L\,\omega} \qquad [4.1]$$

The associated values of the constants are taken from [9]. As the sensing medium, analyte layer is placed above the gold layer. PML is the outmost layer. PML and analyte layer's width are 0.6 μm and 465 nm individually. After the convergence test analyte layer's depth is established which improves the simulation results and accuracy. The thickness of analyte layer was varied from 420 nm to 510 nm. The increment in analyte layer thickness after 15 nm causes very small variation in the effective index's imaginary part. Contrariwise, more thickness of the analyte layer increases simulation time. So to keep up a stability between simulation speed and simulation results exactness of the, 465 nm is used as the optimal analyte layer thickness.

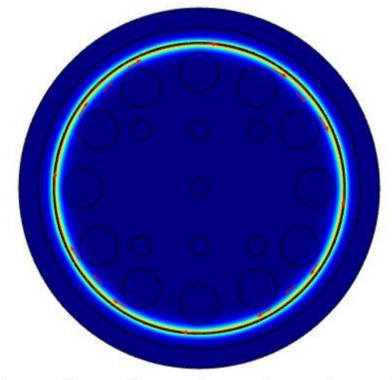
When electromagnetic wave hits the metal field, a joint fluctuation of electrons at the metal dielectric boundary is occurred which is called surface plasmon wave. Core guided mode as well as Surface Plasmon Polariton (SPP) mode has an important contribution to know unknown analyte's RI. Figure 12. (a), (b) & (c) represent x-polarized core mode, y-polarized core mode and SPP mode respectively at analyte RI 1.36, functional wavelength of 0.82 μm.



(a) X-polarization (core mode)



(b) Y-polarization (core mode)



(c) SPP mode

Fig.4.2: Fundamental (a) x-polarized core mode, (b) y-polarized core mode, (c) SPP mode

4.3 Sensor Performance and Optimization

4.3.1 Wavelength sensitivity and resolution

Confinement loss is an important aspect. To determine the loss, imaginary part of the refractive index (neff) is used; its equation is taken from [17].

$$L_c\,(\text{dB/cm}) = 8.686\times k_0\,\text{Im}[n_{eff}]\times 10^4 \qquad [4.2]$$

Where $I_m[n_{eff}]$ is refractive index's imaginary part with unit dB/cm.

Variation for optimum design:

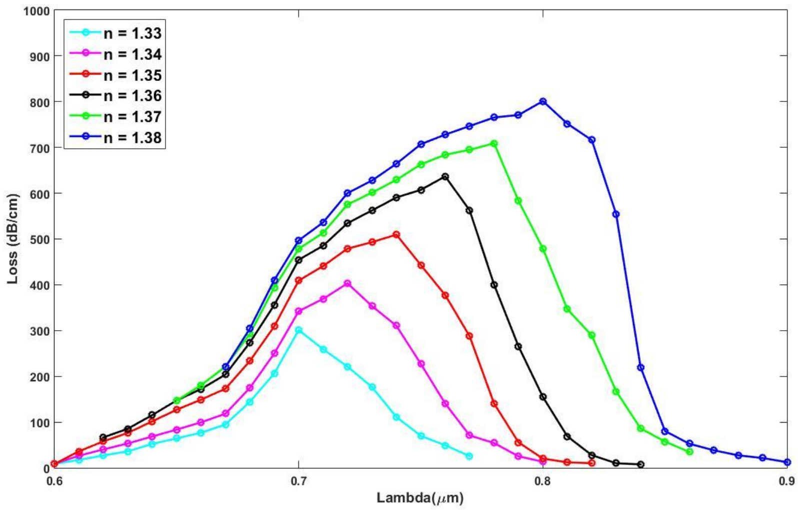


Figure 4.3: Loss spectrum with RI

Figure 4.3, shows the confinement loss deviation with the alteration of refractive indices for 1.8 μm pitch, 0.3 and 0.6 μm air hole diameters and 35 nm gold coating.

The consistent loss is 301.56 dB/cm at RI 1.33 in the wavelength 700 nm. It is observed that when the analyte RI is increased from 1.33 to 1.38 (having step size 0.01), the peak loss depth is also increased. The substantial change of confinement loss occurs as analyte RI incremented. When analyte RI rises the index difference among core and SPP mode turns to be lesser. Furthermore, increase in the analyte RI (a shift is noticed) alters the point of identical phase to upper wavelengths. Loss depths are 403.08, 509.45, 636.68, 709.14, 801.14 dB/cm orderly at refractive indices 1.34, 1.35, 1.36,1.37 and1.38 in the wavelengths 720, 740, 760,780 and 800 nm respectively. Enhanced confinement is directed by the high loss depth that increases the intrusion of field across the cladding section. For this, advanced energy shifts from core mode to the SPP mode and interaction with analyte enhances. The resonance wavelength shifts are 20 with analyte RI varied from 1.33 to 1.34, 1.34 to 1.35, 1.35 to 1.36, 1.36 to 1.37, 1.37 to 1.38 individually. Resonance wavelength move causes sensitivity that can be computed by using wavelength interrogation method. From [24] the equation of wavelength sensitivity is taken.

$$S_{\lambda}(nm/RIU) = \Delta\lambda_{peak} / \Delta n_a \quad [4.3]$$

Where λpeak means peak wavelength shift for analyte RI variation, Δna is the difference between two sequential analyte RI. The theoretical wavelength sensitivities are obtained as 2000 nm/RIU at 1.33, 1.34, 1.35, 1.36 and 1.37 respectively. Another important parameter is sensor resolution. It can be achieved by using wavelength interrogation method. We used the equation of sensor resolution from [17].

$$R(RIU) = \Delta n_a \times \Delta\lambda_{min} / \Delta\lambda_{peak} \quad [4.4]$$

4.3.2 Amplitude sensitivity

The implementation of wavelength interrogation method is expensive as it provides sensitivity at specific wavelength only. But amplitude sensitivity does not require

Wavelength interpolation and so it is simple and economic. The equation of amplitude sensitivity is taken from [48].

$$S_A(RIU^{-1}) = -\frac{1}{\alpha(\lambda, n_a)} \frac{\partial \alpha(\lambda, n_a)}{\partial n_a} \quad [4.5]$$

From this equation, the amplitude sensitivity of the sensor is known. The greater the sensitivity, the better the result will be.

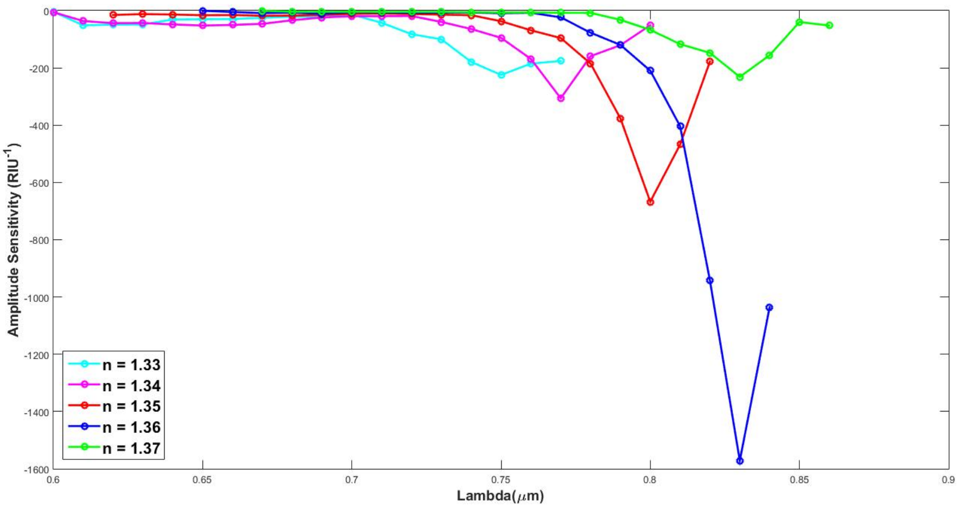


Figure 4.4: Amplitude sensitivity with RI variation for optimum design.

Figure 4.4, depicts amplitude sensitivity of 250, 390, 650, 1550,210 RIU−1 respectively for 1.33, 1.34, 1.35, 1.36, and 1.37 RIs and optimal parameters.

Hence, best result can be found for the 1.36 RI as in this one, best result for amplitude sensitivity was found with the gold layer being 35 nm in each case.

TABLE 1: peak loss and amplitude sensitivity for various refractive index with the same gold layer thickness

REFRACTIVE INDEX	GOLD THICKNESS(nm)	PEAK LOSS (db/cm)	AMPLITUDE SENSITIVITY (RIU^-1)
1.33	35	301	250
1.34	35	403.08	390
1.35	35	509.49	650
1.36	35	636.68	1550
1.37	35	709.14	210
1.38	35	801.14	NA

4.3.3 Gold thickness variation

Alteration of gold layer width has visible impact on loss depth and amplitude sensitivity

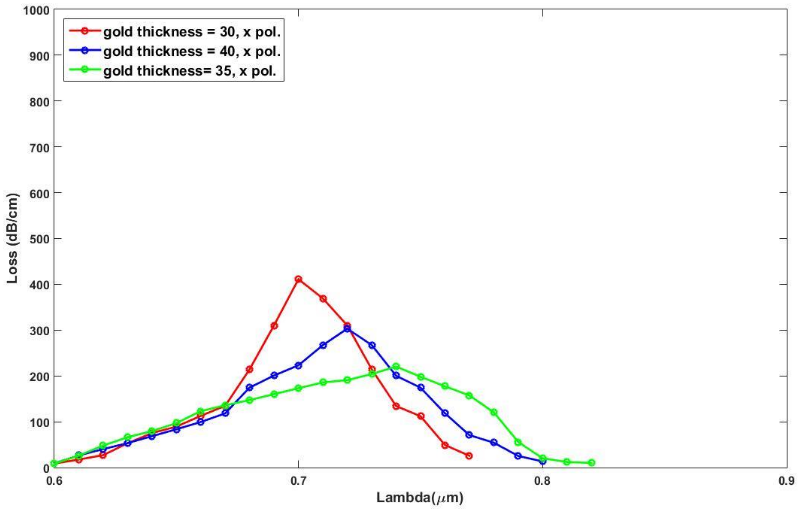


Figure 4.5: confinement loss with gold layer thickness variation for optimum design (x polarization)

Figure 4.5 Shows that at RI 1.36, the confinement losses are 411, 220 and 303.08 dB/cm when the depth of gold layer is correspondingly 30, 35 and 40 nm. So, loss is declined this time. Here we get the least loss for 35 nm, these are for X-polarization.

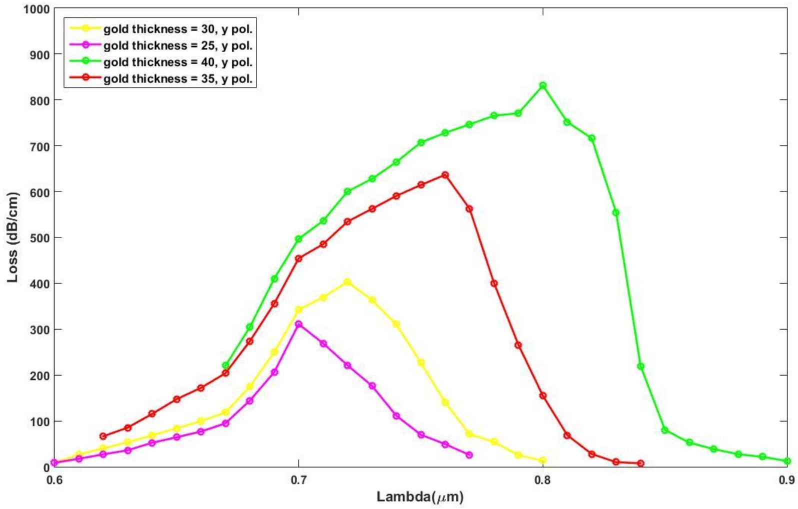


Figure 4.6: confinement loss with gold layer thickness variation for optimum design (y polarization)

It shows that at RI 1.36, the confinement losses are 305, 377, 605 and 812 dB/cm when the depth of gold layer is correspondingly 25, 30, 35 and 40 nm. These are all for Y-polarization. So, we continued our work progress with X-polarization

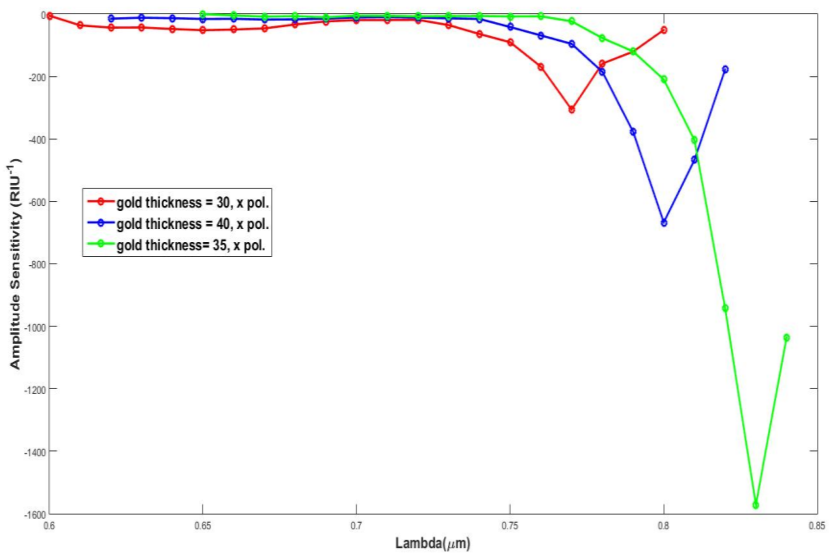


Figure 4.7: Amplitude sensitivity with gold layer thickness variation for optimum design (x polarization)

Shows that at RI 1.36, the amplitude sensitivity are 190, 1607 and 650 RIU^{-1} when the depth of gold layer is correspondingly 30, 35 and 40 nm. These are all for X-POLARIZATION

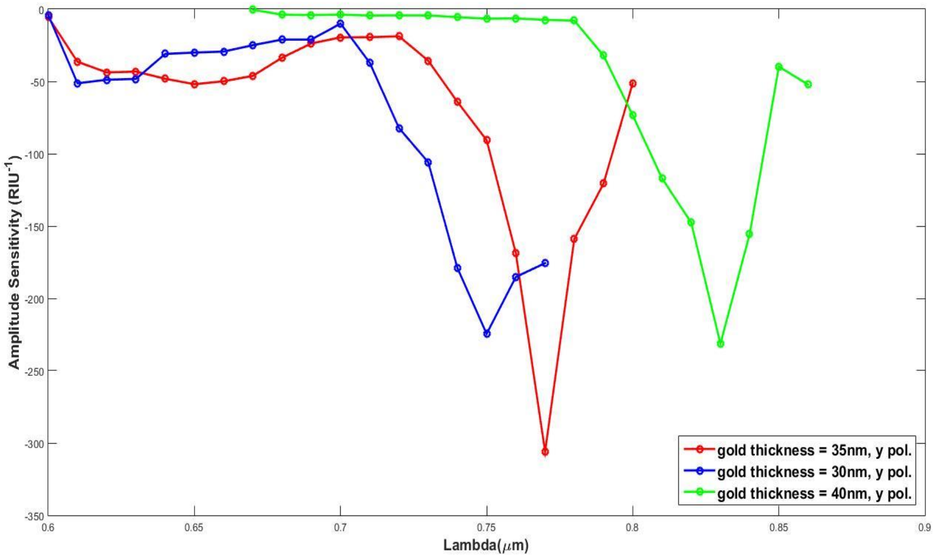


FIGURE 4.8: Amplitude sensitivity with gold layer thickness variation for optimum design (y polarization)

It shows that at RI 1.36, the amplitude sensitivity are 180, 47, 55 RIU^{-1} when the depth of gold layer is correspondingly 30, 35 and 40 nm. These are all for Y-POLARIZATION, which is a very poor one.

And the best result was found for the gold layer thickness of 35nm as the most sensitivity was found there. (table 2)

Seeing the above result, we continued our work with X-POLARIZATION

TABLE 2: PEAK LOSS AND AMPLITUDE SENSITIVITY FOR DIFFERENT GOLD THICKNESS AND A FIXED REFRACTIVE INDEX (X-POLARIZATION)

GOLD THICKNESS(nm)	**REFRACTIVE INDEX**	**PEAK LOSS (db/cm)**	**AMPLITUDE SENSITIVITY (RIU^-1)**
30	1.36	411	190
35	1.36	220	1607
40	1.36	303.08	650

4.3.4 PML Depth Variation

Alteration of PML depth has visible impact on loss depth and amplitude sensitivity.

It shows confinement losses are 392.45, 487, 12, 587.43 and 695.87 dB/cm respectively for 0.2, 0.6,1 .0 and 1.2 um. PML depths and optimal parameters.

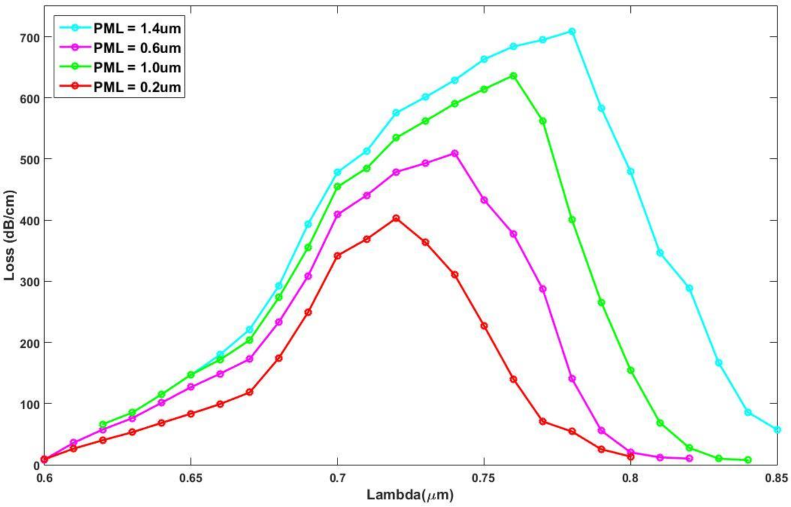


Figure 4.9: confinement loss with PML depth variation for optimum design

Hence, best result can be found for the 0.6 um as in this one, best result for amplitude sensitivity was found with the gold layer being 35 nm in each case.

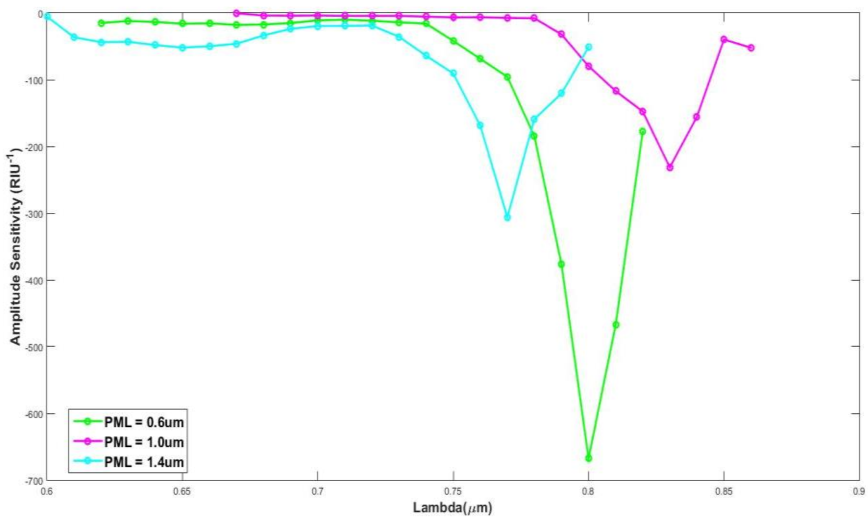


FIGURE 4.10: Amplitude sensitivity with PML depth variation for optimum design

It shows that at RI 1.36, the amplitude sensitivity are 698, 237, 305 RIU−1 when the depth of PML layer is correspondingly 0.6, 1 and 1.4 um.

TABLE 3: peak loss and amplitude sensitivity for different PML depth having the same RI and gold layer thickness

PML(um)	GOLD THICKNESS(nm)	REFRACTIVE INDEX	PEAK LOSS (db/cm)	AMPLITUDE SENSITIVITY (RIU^-1)
0.2	35	1.36	392.45	NA
0.6	35	1.36	487.12	698
1.0	35	1.36	587.43	237
1.4	35	1.36	695.87	305

So, from the above result, it is found that we have the best for both loss and amplitude sensitivity for 0.2 um PML depth.

4.4 Achievements through the thesis work

In thesis work, we have designed a low cost and small sized high sensitive PCF based SPR Sensor .The main outcomes of this thesis are given below:

- Increasing the sensitivity
- Developing fabrication process and make it more practical
- Higher Resolution
- Proper and rapid dynamic detection
- Low cost most economical sensor
- Higher wavelength shifting
- Real time sensing
- Higher confinement
- Decreasing the size of the sensor
- Simplicity of the design

4.5 Limitation of the proposed biosensor

- Due to fabrication challenges, PCF based sensors have limited practical applications.
- Most of the investigations were performed theoretically
- As PCF-based sensors are mainly employed in lab-oriented researches,
- For detecting large amount of biological and biochemical analytes, it needs to overcome some difficulties.
- Higher confinement loss can a problem
- Detection process is relatively slow

Chapter 5

Conclusion, Recommendations and Future Work

5.1 Conclusion

In a word, it can be said that PCF based SPR Bio sensor is a vital element to sense biochemical or biological analyte. We can easily detect unknown analyte by this type of bio sensor. Before the invention of this type of bio sensor, prism based SPR sensor was used which has some defects such as-

- Huge in size
- Difficult to detect
- Lower Resolution
- Lower Sensitivity
- Chemically Unstable
- Lower Wavelength Shift
- Complex Design
- Difficult for dynamic detection
- Lower Confinement
- Difficult for practical fabrication

But this this kind of problems have been bewildered by PCF based SPR Sensors. PCF based SPR Sensors have some legionary advantages or facilities are given below:

- small in size
- Easier to detect
- Higher Resolution

- Chemically stable by using Gold as an external layer which is chemically
- viable metal
- Higher Sensitivity
- Higher Wavelength Shift
- Larger range of variation of refractive index
- Simple Design
- Having a practical fabrication
- Higher Confinement
- Dynamic Detection

The value of sensitivity defines how accurately a sensor can sense. Using wavelength interrogation method and amplitude interrogation method sensitivity of a sensor is measured. At recent times highly sensitive sensor with excellent resolution is very demandable. Sensors which show linear appearances with high sensitivity are more attractive.

A simple PCF based SPR sensor is proposed in this work. This sensor offers higher sensitivity and improved resolution. Here, gold is used as plasmonic material used an external layer which is highly chemically stable. Both analyte layer and gold film are positioned at exterior surface of the PCF. The prime reasons are to minimize the fabrication difficulty and to have more practical sensing. Performance parameters are also investigated in this paper. Proposed sensor shows maximum wavelength sensitivity nm/RIU and amplitude sensitivity RIU-1 using optimized sensor parameters. This proposed sensor has dynamic detection range. It is studied that our proposed sensor can response at refractive index range from 1.33 to 1.38.

5.2 Future Recommendations and Outcomes

There are some works needed to do for the better improvement of our recent works. These works are described below:

Future Outcomes and recommendations

1. New design with improved performance can be implemented
2. SPR sensing technologies for THz frequencies can be advanced.
3. Implementing this design by adding alternative plasmonic material (silver, titanium etc.) outside the PCF surface.
4. Need to work for the improvement of resolution
5. Need to work for the improvement of sensitivity
6. PCF based sensor which can sense numerous refractive indices can be examined in future.

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