Performance Analysis of Surface Plasmon Resonance Waveguide for Sensing Applications

A Thesis

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

Doctor of Philosophy

in

Department of Electronics and Communication Engg.

by

Pradeep Kumar Teotia
(Reg no: 951306002)

under the supervision of

Dr. R. S. Kaler
Senior Professor

Thapar University
Patiala, India
July 2017

Candidate Declaration

I hereby certify that the work, which is being presented in the thesis, entitled **Performance Analysis of Surface Plasmon Resonance Waveguide for Sensing Applications**, in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in Electronics and Communication Engineering from Thapar University, Patiala is an authentic record of my own work carried out during the period **July 2013** to **July 2017** under the supervision of Dr. R.S. Kaler. I have also cited the reference about the text(s)/figure(s)/table(s) from where they have been taken.

The matter presented in this thesis has not been submitted elsewhere for the award of any other degree or diploma from any institution.

Date: 18.12.17

Pradeep Kumar Teotia
Candidate

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

Date: 18.12.17

Dr. R. S. Kaler
Senior Professor
Supervisor

.........dedicated to my fufaji "Late Shri Kushal Pal Singh Rajora"

Abstract

Non-contact type of measurements with the help of optical technologies in the field of sensing and instrumentation has become a revolutionary idea in the present scenario. The advanced feature of optical fiber/waveguide such as exceptional sensitivity and accuracy towards external environment has made research arena inevitable and forced us to develop a new thought. This property has given a way to a new variety of optical sensors which are free from electromagnetic interference. In parallel to these advantages, optical sensor technology has a perfect coordination between optoelectronic and fiber optic communication industry. Current scenario observes an improved quality of optical sensors which thereby increases the possibility to replace traditional sensors. Presently numerous research work is undertaken using fiber optic sensors with different interrogation techniques. Consequently, combination of optical fiber with material technology has also opened a new field to sensing platform. This thesis highlights the basic theory, fundamentals of SPR technology and the phenomena of SPR biosensor. This thesis also presents a new idea of performance analysis of Surface Plasmon Resonance waveguide for sensing applications. Multilayer grated structure is herby proposed as simple as versatile waveguide sensors. We further discuss the current developments and future applications of SPR based waveguide sensor.

Different structures & geometry of grating and multilayer methods is investigated. The work gives an insight about the scope of metal slotted dielectric waveguide with a high refractive index material in which surface plasmons can propagate. Study of several symmetrical metal dielectric metal structures, it is analysed that slot waveguide geometry shows many intriguing properties with the use of high refractive index material that are not shown in the single interface metal dielectric. The surface plasmon resonance of slot MDM waveguide are studied and simulated using finite difference time domain method. High sensitivity ($\approx 200 RIU^{-1}$) is exhibited by the proposed slot MDM waveguide geometry ($\approx 200 RIU^{-1}$) and higher transmission ($\approx 10\%$) is also obtained. Geometry with different dielectric materials i.e. Air, Silicon-di-Oxide (SiO_2) etc. has been investigated. The transmission has also been compared for slot MDM structures for different combinations Au $-$ Si Air Au or vice versa.

In multilayer grated structure, periodic gratings within the waveguide is inscribed in such a way that light prorogating inside the waveguide can interact with the surrounding environment, thus resulting in an output spectrum that includes changes due to the presence of all external parameters. Factors affecting the refractive index sensitivity are explored

through theory and simulation. Adding grating to the structure brings two advantages, firstly light can be coupled into surface plasmons by providing necessary phase matching and secondly they may further perturb the propagation of the surface plasmons. One of the main aim of the present work is to study the different geometries to explore the sensitivity and detection accuracy. We observed certain transmission characteristics for the respective designs. This thesis investigates the high performance of periodic grating coupled multi-layered SPR waveguide based on combination of aluminium and gold (Al+Au). High sensitivity is obtained by using grating filled with silver instead of air. Sensors performance is analysed by optimizing width and thickness of SPR active metal layer as well as the grating period. Using FDTD method, sensitivity and detection accuracy can be improved using appropriate multi-layered grating configuration in proportion.

Grating based surface plasmon resonance waveguide biosensor for the detection of lung cancer biomarkers using Vroman effect is also reported. The proposed grating based multilayered biosensor is designed with high detection accuracy for Epidermal growth factor receptor and is also analysed to show high detection accuracy with acceptable sensitivity for lung cancer biomarkers i.e. CEA and EGFR. The introduction of periodic grating with metal multilayer generates a good resonance that helps in early detection of lung cancerous cells. Using finite difference time domain method, it is observed that wavelength of biosensor get red-shifted on variations of the refractive index due to the presence of both the lung cancerous bio-markers.
The observed detection accuracy and sensitivity of proposed biosensor is quite acceptable for both lung cancer biomarkers i.e. Carcinoembryonic antigen and Epidermal growth factor receptor which further offer us label free early detection of lung cancer using these biomarkers. These sensors offer several advantages in bio-chemical sensing, chemical & food processing. The study suggests that SPR waveguide is useful for developing good sensitive systems. Most of the research findings of the thesis have been published in various SCI based international referred journals as per publication list.

List of Publications

International Journal

1. Pradeep Kumar Teotia, R S Kaler, *"Exploitation of slotted multilayer coatings for the enhancement of light transmission and sensitivity through surface plasmon resonance waveguide"*, Journal of Nanoelectronics and Optoelectronics, volume 11, issue 3, pages 311-314, Jun 2016.

2. Pradeep Kumar Teotia, R S Kaler, *"Multilayer with periodic grating based high performance SPR waveguide sensor"*, Optics Communications, volume 395, pages 154-158, July 2017.

3. Pragya Saxena, Pradeep Kumar Teotia, R S Kaler, *"Effect of different TM modes on the sensitivity of surface plasmon resonance based optical fiber sensor"*, Journal of Optoelectronics and Advanced Materials-Rapid Communications (OAM-RC), volume 10, issue 5-6, pages 343-346, May 2016

4. Pradeep Kumar Teotia, R S Kaler, *"1-D Grating based SPR biosensor for the detection of lung cancer biomarkers using Vroman effect"*, Optics Communications. [In Press]

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Last but not the least, my Reverend Fufa ji (**Sh. Kushal Pal Singh Rajora**) who is not alive to see my work, but whose blessings have brought me to this platform - I thank him.

Pradeep Kumar Teotia

Table of Contents

List of Figures

List of Tables

List of Notations

α	Attenuation Constant
Ag	Silver
Al	Aluminum
Au	Gold
β	Propagation Constant
Λ	Grating Period
ϵ_m	Permittivity of metal
ϵ_d	Permittivity of dielectric
μ	Permeability
ω	Angular frequency
λ_{Bragg}	Bragg Wavelength
n_{eff}	Effective Refractive index

List of Abbreviations

AOTF	Acousto Optical Tunable Filter
APM	Argument Principle Method
ATR	Attenuated Total Reflection
CEA	Carcinoembryonic Antigen
DA	Detection Accuracy
DDM	Double Dip Method
EGFR	Epidermal Growth Receptor
FDTD	Finite Difference Finite Domain
FWHM	Full Width at Half Maximum
NA	Numerical Aperture
POC	Point of Care
PA	Protective Antigen
RI	Refractive Index
RIU	Refractive Index Unit
SNR	Signal to Noise Ratio
SOI	Silicon on Insulator
SPP	Surface Plasmon Polariton
SPR	Surface Plasmon Resonance
TIR	Total Internal Reflection
TE	Transverse Electric
TM	Transverse Magnetic
WM	Waveguide Mode

Chapter 1

Introduction

1.1 Introduction

During the last three decades, the emerging need of accurate and fast means of data processing and detection has evolved the research and development of all optical components. This in turn has led to develop a variety of new optical sensing devices which are able to detect and process the measurands using electromagnetic radiation. Further, fabrication techniques and advance material technology has forced us to develop devices with fine structural details. In addition to that, these small developments in optical fields have brought a new era where all conventional mechanical and electrical sensors got a replacement [1, 2, 3].

The motivation behind encouraging the research in the said field is that optical sensing has significant advantages over conventional sensing like electromagnetic interference, robustness etc. Apart from these optical sensing have more advantages over non-optical sensing i.e. small size, enhanced sensitivity, dynamic range and multiplexing capabilities [4, 5]. Besides this, an instrument is a device that is used in measuring or indicating performance, physical quantities or conditions, direction, position, whereas sensors are devices that can detect physical variables, such as pressure, temperature or motion, and have the ability to give a measurable output that varies in relation to the characteristics of the physical variable [2, 6].

In parallel with these developments, optical fiber sensor technology has been a major user of electronic and optical fiber communications industries. Optical fiber sensor applications uses many components that are associated with these industries [7, 8]. The general principle of optical sensor is that light from a led/laser or from a super luminescent source is passed through an optical waveguide which experiences fine changes in its parameters.

In a waveguide sensor, one or more characteristics of a propagating light wave is altered and related to an externally-induced physical or chemical parameter [9]. Optical fiber/waveguide can be used as a sensor to measure pressure, temperature, strain and other quantities by modifying a waveguide so that the quantity to be measured modulates the phase, polarization, intensity and transit time or wavelength of light within the waveguide [10, 11]. Moreover, development of optical sensors for detection of biological and chemical quantities has attained considerable drive and number of researchers have also reported the usage of optical bio-sensors for detection of analytes pertaining to the environmental monitoring, food safety & security and medical diagnostics [12, 13, 14]. In current research work, detection for chemical concentrations as well as medical diagnostics has been carried out.

1.2 Optical Sensing Technology

The scope of development in optical fiber technology has changed the telecommunication industry. Advancements and reduction in the cost of optoelectronic components has changed the approach of scientists and researchers to outlay new product areas. Continuous efforts on reducing the material and dispersion loss, better sensitivity and detection of losses has led to the development of optical sensing technology where one can sense the changes in intensity, wavelength & phase from external perturbations on itself either by using fiber or waveguide. Subsequently, the concept of optical sensing was born. Further,this technology is associated with inherent advantages like light weight, low power and high sensitivity, resistant to electro magnetic interference, small size and environmental ruggedness however,one of the major disadvantage is end user unfamiliarity and cost.

Main driving force for the subsequent development and support for this industry is its ability to replace the traditional sensors due to aforesaid advantages. Optical sensing in simple words can be defined as sensing where variation of the intensity of light is applied. The basic structure of optical sensing system consists of an optical source (LED, Laser diode etc.), modulator or sensing and an optical detector (Optical Spectrum Analyzer, Optical Spectro meter) as shown in fig 1.1 [15]. While based on sensing applications, an optical sensor can be grouped as extrinsic and intrinsic. In an extrinsic optical sensor, light is simply carried to and from external light source through a waveguide where sensing takes place. In such type of cases, optical waveguide is used to get light to the sensing location. Further in intrinsic sensors, perturbations change some characteristics of light inside the waveguide as shown in fig 1.2. Depending upon the extrinsic and intrinsic optical sensors, a detailed comparison of both the types of sensors is detailed below [7]

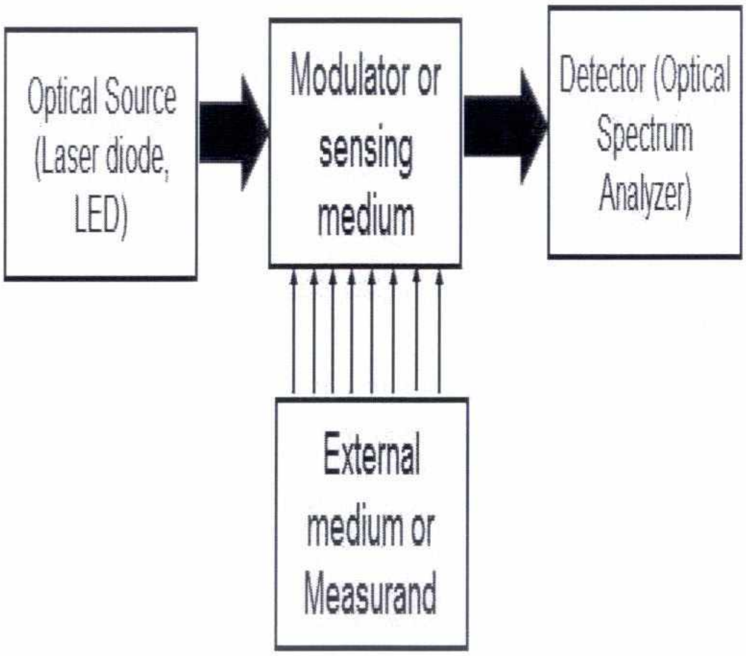

Figure 1.1: Simple Structure of Optical Sensing

Table 1.1: Comparison between the intrinsic and extrinsic sensors

Parameters	**Extrinsic Sensor**	**Intrinsic Sensor**
Application	Temperature, Liquid level & Pressure	Acceleration, Acoustic Pressure, Strain & Vibration
Senstivity	Less	More
Multiplexed	Easily	Difficult to multiplex
Cost	Less Expensive	Expensive
Flexibility	Easier to use	More elaborate signal demodulation

On the other hand, based on applications, an optical sensor can be further classified as [15, 16]

- Chemical Sensor
- Physical Sensor
- Biomedical Sensor

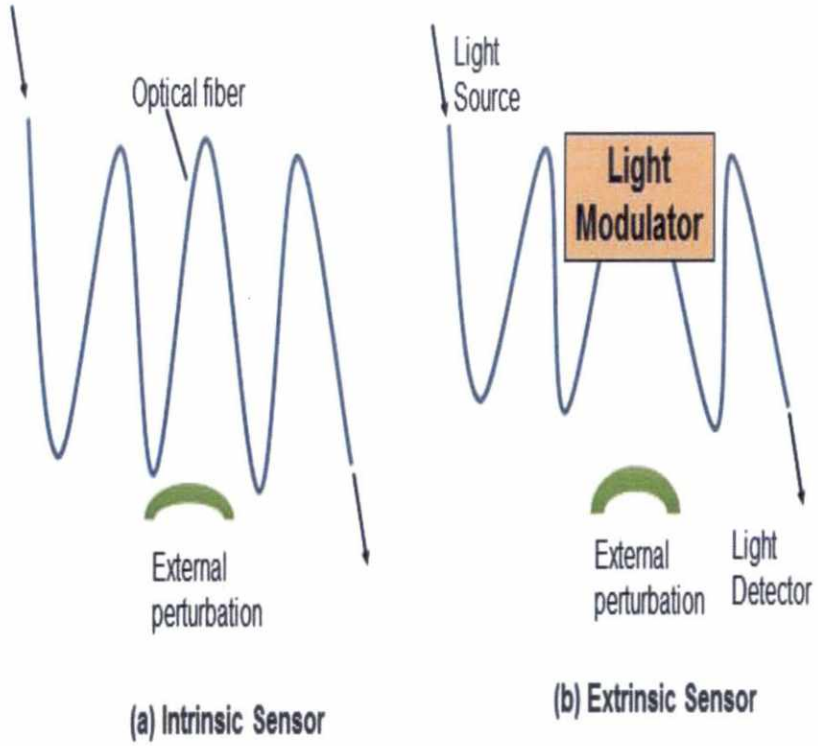

Figure 1.2: Sensing operation of Intrinsic & Extrinsic sensor

Generally, optical sensors can be categorised based on operating principle or modulation, sensing location and the application. Based on modulation process or operating principle, optical sensors further can be classified as below

- Intensity fiber optic Sensor
- Phase fiber optic Sensor
- Frequency fiber optic Sensor
- Polarization fiber optic Sensor

1.2.1 Intensity based sensors

Intensity based optical sensors require more light and usually use large core. To achieve this type of sensors, various type of mechanisms such as attenuation, microbending loss & evanescent fields have been used so that a change in propagated optical intensity can be produced. Microbend sensor is one such intensity based optical sensor which works on the

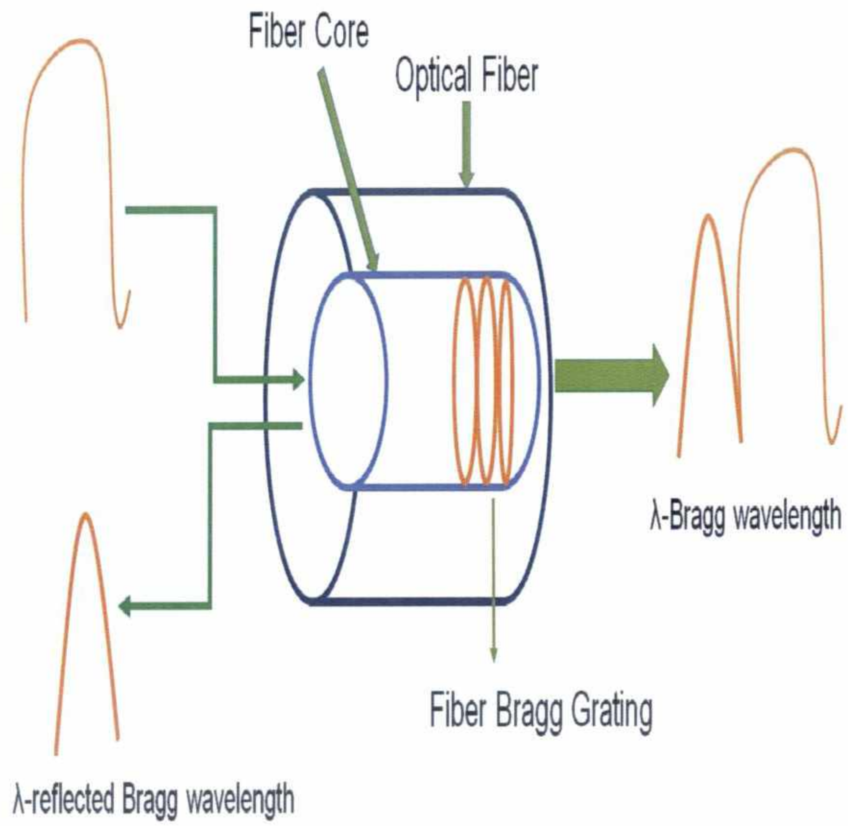

Figure 1.3: Sensing Operation of Fiber Bragg Grating Sensor

principle of periodic mechanical micro bends that can cause the guided modes to couple with radiation modes and result in attenuation of transmitted light. In continuation with this, evanescent wave sensor is one another type of intensity based sensor which uses the light energy that leaks from the core into the cladding. This type of sensor is well known for the measuring of chemical concentration [17].

1.2.2 Wavelength modulated sensors

Wavelength modulated sensors detect changes in wavelength of light. Examples of wavelength modulated sensors are black-body sensor, fluorescence sensor and Bragg-grating sensor. These type of optical sensors are widely used for humidity measurement, medical diagnostics and chemical sensing etc. The most successive and widely used sensor is Bragg grating sensor which is also termed as Fiber Bragg grating sensor. The detailed sensing operation is shown in fig 1.3. By imposing periodic changes in refractive index of the core, Bragg gratings has been formed. The grating is used for light propagation and a part of signal is reflected back at a particular wavelength which is called as Bragg Wavelength λ_{Bragg}. This implies that Bragg grating is also an effective filter [18]. Another type of wavelength-modulated sensor is black-body sensor that uses a black body cavity at the end of the fiber. When the temperature of the cavity rises, it starts glowing and act as a light source. Basically this type of sensors are used to measure the temperature under strong RF fields [19].

1.2.3 Phase modulated sensors

Phase modulated sensors use the phenomena of phase changing for the detection of light. The operation involves the comparison of the phase of light in the waveguide with the reference device. To achieve this, interferometer is required. Commonly used interferometers are Mach-Zehnder, Fabry-Parot, Michelson and grating interferometers. There are some differences as well as similarities between the Michelson and Mach-Zhender interferometers like michelson have better senstivity than Mach-Zhender while Mach-Zhender requires two optical fiber as compared to Michelson [20].

1.2.4 Polarization modulated sensors

The portion of electric field direction of the light field is defined as the polarization state of the light field. Different types of polarization states are detailed below [7]:

- Linear - The direction of electric field in the same line during the propagation of light.
- Elliptical - Electric field forms an elliptical shape during the light propagation.
- Circular - Electric field direction emerge in a circular shape during the light propagation.

1.3 Surface Plasmon Resonance

Optical sensors belong to the group of refractometric based sensors i.e. Bragg grating sensor, integrated optical Mach-Zhender interferometer and the white light interferometer that measures the change in parameters with the respect to change in refractive index in the field of electromagnetic wave supported by optical geometry. Based on this principle, excitation of surface plasmons is termed as surface plasmon resonance [21]. The basic idea of surface plasmon resonance was first demonstrated in early nineties using metal diffraction gratings by Wood. Further, Fano has also brought up the association of these anomalies of diffractions with excitation of electromagnetic wave [22, 23].

1.3.1 Principle

Plasma oscillation is the phenomena where free electrons in the metal oscillates cooperatively from their equilibrium position where the positive charge of metal (atomic nucleus or jellium that the positive charges are averaged) bind the ensemble of the free electrons. Plasmon means the quasi-particle representation of plasma frequency. The surface plasmon is the plasma oscillation that localizes at the surface or interface. These charge density oscillations along the metal-dielectric interface are known as surface plasma oscillations. A metal-dielectric interface supports plasma oscillations. The quantum of these oscillations is termed as a surface plasmon mode or surface plasmons. These surface plasmons are accompanied by p-polarized wave or longitudinal electric field, which decays exponentially in dielectric as well as metal in fig 1.4. Due to this exponential decay of field intensity, the field has its maximum value at metal-dielectric interface itself [24, 25].

Basically there are two types of surface plasmons. (a) Long Range Surface Plasmons (b)Short Range Surface Plasmons. Earlier we have studied that surface plasmons exists on the metal dielectric surface. If the width of metal layer is thin and metal is sandwiched between two dielectrics, then it is supposed that coupling between the surface plasmons at both the boundaries occur which further give rise to mixed modes of electromagnetic field i.e. symmetric and antisymmetric surface plasmons. The symmetric surface plasmons have a attenuation (α) and linear propagation constant (β) which both follow increasing trend with increasing the metal layer thickness [26]. While attenuation and propagation constant of antisymmetric surface plasmons decrease with increasing the metal layer thickness. Symmetric surface plasmons have less attenuation in comparison to the antisymmetric surface plasmons. So such type of surface plasmons are termed as Long range

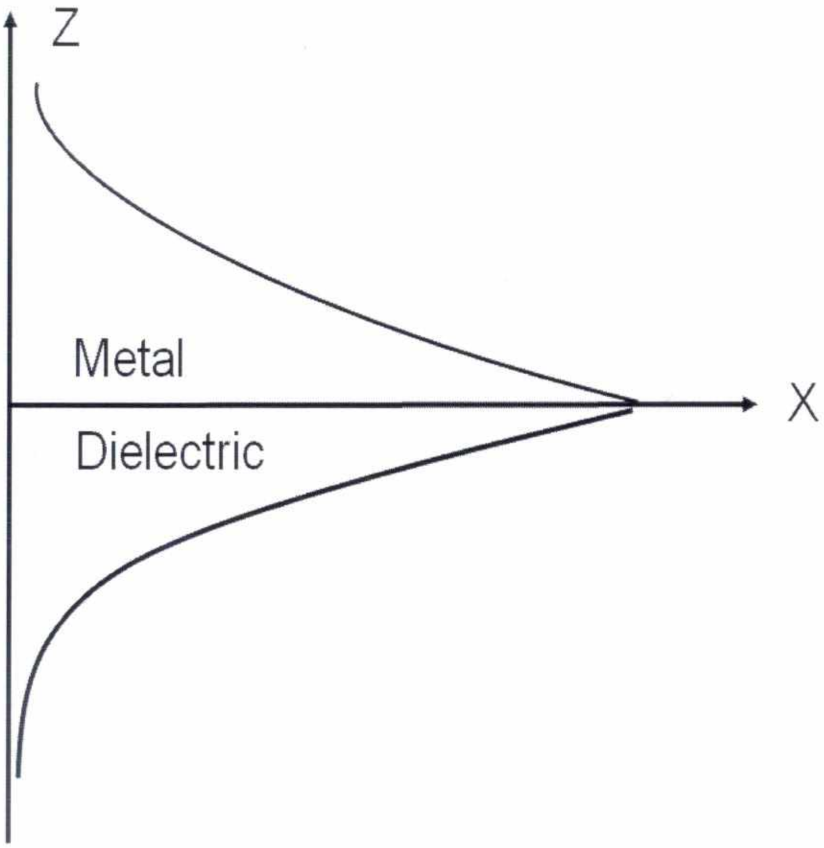

Figure 1.4: Exponential decay of field intensity in metal and dielectric system

surface plasmon, whereas antisymmetric mode of surface plasmons are known as a short range plasmon [27, 28]. In continuation to this, two basic configurations were proposed to recognize the basic theory of surface plasmon resonance at the metal-dielectric interface. The detailed description will be discussed in the next section 1.4.

1.3.2 Minimum of Reflectance at Resonance

The excitation of surface plasmons at metal-dielectric interface results in the transfer of energy from incident photons to surface plasmons, which reduces the energy of the reflected light. If the normalized reflected intensity (R), which is basically the output signal, is measured as a function of wavelength (λ_{res}) by keeping other components and parameters (such as dielectric layer, and metal layer) unchanged, then a sharp dip is obtained at resonance wavelength λ_{SP} due to an efficient energy transfer to surface plasmons. The light wave is normally incident at an angle greater than the corresponding ATR angle. At this point, the law of energy conservation is applied which states that

T+A+R = 1, i.e., the sum of relative absorption (A), transmission (T) and reflection (R) is unity. Since T = 0 at ATR, the light wave passing through the glass prism ϵ_p, is reflected partially at prism-metal interface.

A remaining part of the incident light wave energy is termed as exponentially decaying evanescent wave as this light wave traverses around the metal film. Due to this, surface plasmon get excited at the metal-dielectric (m/d) interface, which further radiates light back into the metal film. Subsequently, back scattered field tends to increase when thickness of metal layer is kept small. Since, the backscattered field wave is out-of-phase with the incoming wave, these two interfere destructively and cause reflectance (R) to reduce. If, the thickness of metal layer is kept minimum then, both backscattered field and incoming wave is compensated and reflectance becomes equal to zero. On the other hand, if radiation field is seized in metal film, then absorbance is almost equal to 1. Similarly, if metal layer thickness is getting larger than the backscattered field disappears as a result of this reflectance approaches to 1 and absorption of incident light wave does not take place. It is also concluded that value of reflectance depends on the combination of metal layer thickness, angle of incidence and incident light frequency. Finally reflectance (R) can be termed as a function of resonance wavelength λ_{res} at the prism-metal interface [24, 25].

1.3.3 Surface Plasmons on Metal-Dielectric Interface

In view of the above, surface plasmons can exists in semi-infinite metal having complex permittivity $\epsilon_m = \epsilon'_m + i\epsilon''_m$ and a dielectric with a permittivity $\epsilon_d = \epsilon'_d + i\epsilon''_d$ where ϵ'_j and ϵ''_j are real and imaginary parts of permittivity (where j is metal (m) or dielectric (d)). By applying Maxwell equations (as detailed below in equations) in association with boundary conditions, it has been revealed that structure can support only guided mode of electromagnetic field termed as Surface Plasmon. Basically surface plasmons is transversally magnetic (TM) modes and plane of interface is perpendicular to the direction of propagation. It also implies that magnetic field intensity is maximum at metal - dielectric interface and decays towards the metal and dielectric. The decaying field at metal - dielectric interface is termed as penetration depth, distance from the interface at which magnetic field amplitude decreases by a factor of e. The propagation constant of metal-dielectric interface can be written as [24]

$$\beta_{SP} = \frac{\omega}{c}\sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}} = \frac{2\pi}{\lambda}\sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}} \tag{1.1}$$

where λ is the wavelength and c is speed of light in vacuum. In context of this, a very important parameter is propagation constant which is denoted by β which is generally used to identify the waveguide modes. Waveguide mode can be expressed by transverse distribution of electromagnetic field along with the direction of propagation. As per fig 1.5, plane wave propagation constant can be defined as $k_0 n_2$ where $k_0 = \frac{2\pi}{\lambda}$. Thus the propagation constants along the x and z direction are as follows in equation 1.2 [29].

$$\begin{aligned} k_x &= k_0 n_2 \cos\theta = h \\ k_z &= k_0 n_2 \sin\theta = \beta \end{aligned} \tag{1.2}$$

Practically guided mode propagating along the z direction is as shown in fig 1.5 with a refractive index of $n_2 \sin\theta$ which is also known as effective refractive index. If N is the no. of the modes, then $\beta = k_0 N$; N $= n_2 \sin\theta$ and accordingly modal attenuation may be expressed as $b = Im\{\beta\}\frac{0.2}{\ln 10}$. Considering the fig 1.5, electromagnetic wave can be described by applying Maxwell equations 1.3 with a propagation constant β [29].

$$\begin{aligned} \vec{E}(x,y,z,t) &= \vec{E}(x,y)\exp\iota(\omega t - \beta z) \\ \vec{H}(x,y,z,t) &= \vec{H}(x,y)\exp\iota(\omega t - \beta z) \end{aligned} \tag{1.3}$$

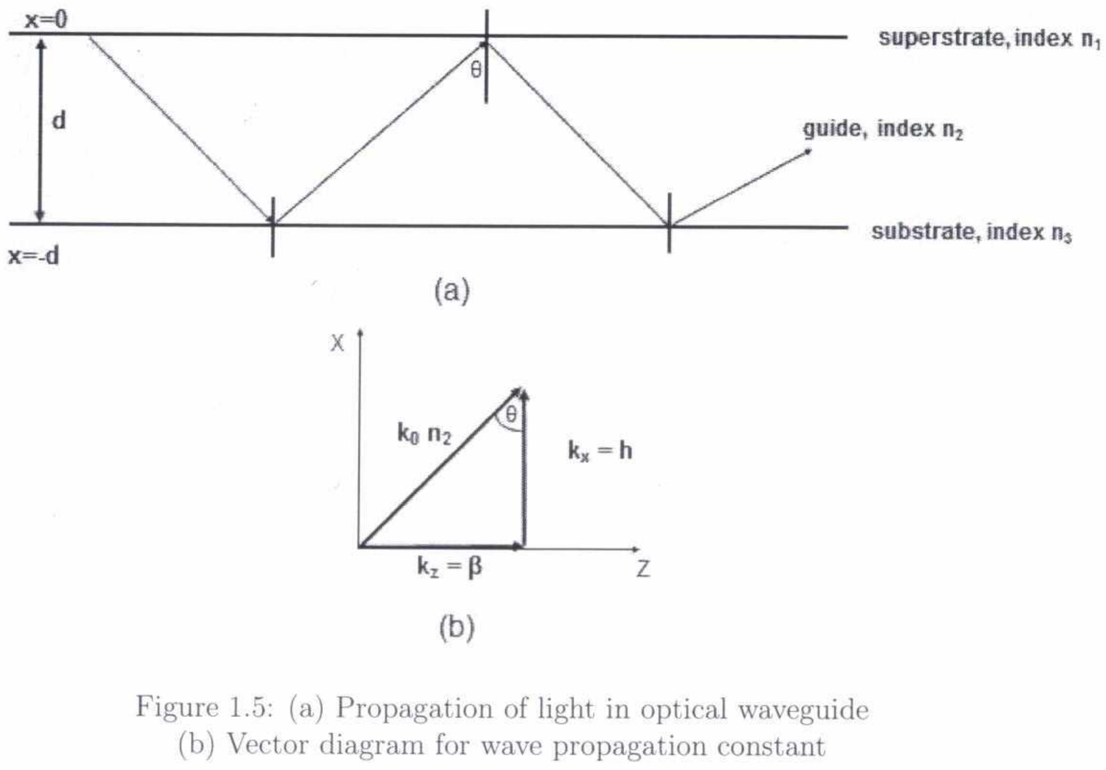

Figure 1.5: (a) Propagation of light in optical waveguide
(b) Vector diagram for wave propagation constant

where $\overrightarrow{E}$ & $\overrightarrow{H}$ are the electric and magnetic fields respectively. As per the geometry of the waveguide, variation of field in y direction is almost nil, therefore using above equation 1.3, $\frac{\partial}{\partial y} = 0$, (also $\frac{\partial}{\partial z}$ = -$\iota\beta$ and $\frac{\partial}{\partial t}$ =ι ω). Maxwell's equation for a lossless and isotropic dielectric medium can be defined as [29],

$$\begin{aligned} \nabla \times \overrightarrow{E} &= -\mu \frac{\partial H}{\partial t} \\ \nabla \times \overrightarrow{H} &= \epsilon \frac{\partial E}{\partial t} \end{aligned} \tag{1.4}$$

where ϵ and μ are the dielectric permittivity and magnetic permeability of the medium respectively and finally we obtain two different modes with orthogonal polarisation modes [29].

$$\begin{aligned} TE: \qquad & E_y = -\frac{\omega\mu}{\beta} H_x \qquad \frac{\partial E_y}{\partial x} = -\iota\omega\mu H_z \\ TM: \qquad & H_y = \frac{\omega\epsilon}{\beta} E_x \qquad \frac{\partial H_y}{\partial x} = \iota\omega\epsilon E_z \end{aligned} \tag{1.5}$$

Equation 1.5 represents transverse electric (TE) and magnetic (TM) mode. While TM contains the components H_y, E_x, E_z as magnetic field having polarisation along the y-direction which is normal to the direction of propagation. For better understanding the solution for TM case is as follows [29];

$$H_y(x, z, t) = h(x) exp\iota(\omega t - \beta z) \tag{1.6}$$

where the field distribution has an exponential decay as x approaches $\pm\infty$ and wave remain in range of -d$\leq$ x $\leq$ 0, (d is the thickness of the waveguide). Therefore the equivalent fields for superstrate, guide and substrate respectively is given in below expression [30].

$$h(x) = \begin{cases} Aexp(-qx) & 0 \leq x < \infty \\ A[\cos(hx) - \frac{q}{h}\sin(hx)] & -d \leq x \leq 0 \\ A[\cos(hd) + \frac{q}{h}\sin(hd)]exp[p(x+d)] & -\infty < x \leq -d \end{cases}$$

Above equation obeys the wave equation for an isotropic, charge free medium and can be expressed as [30]

$$\nabla^2 H_y(x, z, t) + k_0^2 n_j^2 H_y(x, z, t) = 0 \tag{1.7}$$

Based upon the equation 1.6 and 1.7, the calculated wave numbers q, h and p in superstrate, guide and substrate respectively [30]

$$\begin{aligned} q &= \sqrt{\beta^2 - {n_1}^2 {k_0}^2} \\ h &= \sqrt{{n_2}^2 {k_0}^2 - \beta^2} \\ p &= \sqrt{\beta^2 - {n_3}^2 {k_0}^2} \end{aligned} \tag{1.8}$$

By imposing the boundary conditions, the eigenvalue equation has been derived [30].

$$\tan(hd) = \frac{h(p+q)}{h^2 - pq} \tag{1.9}$$

The maximum number of modes, M, that can propagate along the waveguide can be calculated depending upon the condition of phase matching which must be equal to Mπ so that maximum interference occurred and it is also understood by an expression 1.10, $M\pi = hd$ [30].

$$M = \frac{2d}{\lambda}\sqrt{{n^2}_2 - {n^2}_3} \tag{1.10}$$

1.4 Coupling Methods

1.4.1 Prism-coupling

The basic phenomenon of excitation of surface plasmons has been achieved by using a prism coupler and the attenuated reflection method (ATR). There are two configurations which further describe the prism coupling method.

- **Otto Configuration**

  This configuration is working on general concept that involves the coupling of evanescent wave with the surface plasmon wave. It is done by bringing a light beam at the base of coupling prism at an angle which is slightly greater than critical angle θ_{ATR} at prism-air interface [24]. The propagation constant of evanescent wave is always along the said interface and evanescent wave have the nature to decay exponentially in the dielectric medium adjacent to metal layer. Both of these characteristics of evanescent wave are similar to the surface plasmon wave, so there is a strong possibility of interaction between these waves. The x-component of the

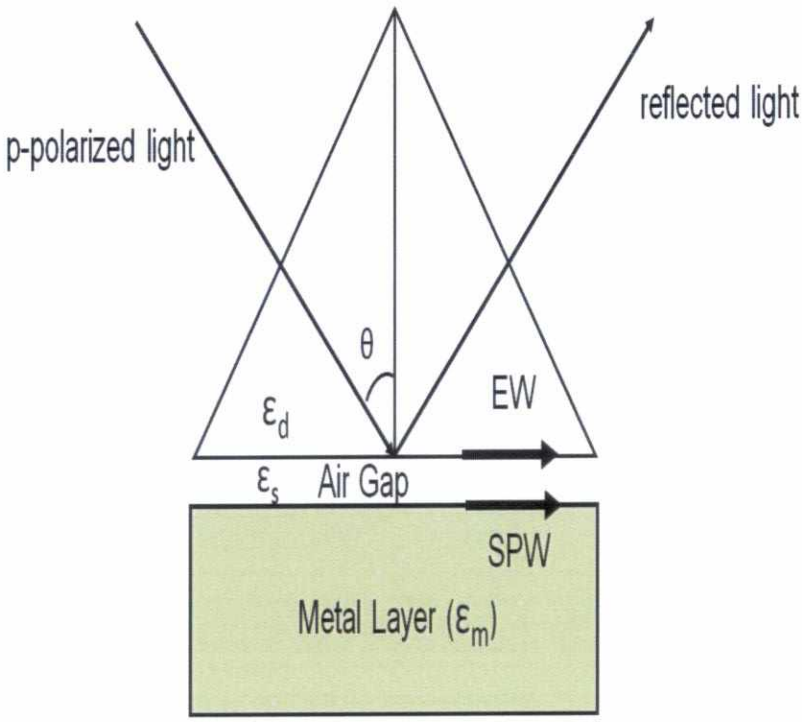

Figure 1.6: Excitation of surface plasmons at metal-prism interface in Otto Configuration

wave i.e. propagation constant at prism-air interface is given by equation 1.11 [24]

$$K_s = \frac{\omega}{c}(\epsilon_p)^{1/2} \sin\theta \tag{1.11}$$

If a metal surface is now brought in contact of this decaying evanescent field in such a way that an air gap remains between the prism base and metal layer, then the evanescent field at prism-air interface can excite the surface plasmons at the air metal interface as shown in fig 1.6. However, this configuration is difficult to realize practically as the metal has to be as near as 200 nm to the prism surface. This approach is found to be very useful in studying the single-crystal metal surfaces and adsorption on them [25].

- **Kretschmann Reather ATR Configuration**

In partial modification or improvement in Otto configuration, Kretschmann and Reather investigated that the metal layer can be used as the spacing layer in place of air, i.e., evanescent wave (A propagating wave which decay exponentially along the metal-dielectric interface due to the occurrence of total internal reflection) is generated at the prism-metal layer interface. It can further excite surface plasmons

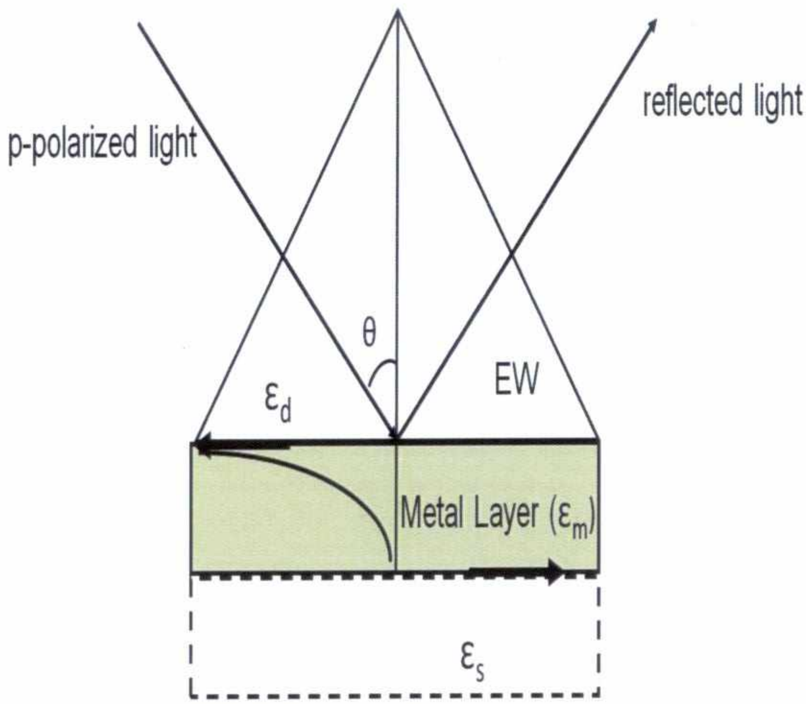

Figure 1.7: Kretschmann configuration for the excitation of surface plasmons

at the metal-air interface by keeping in view that the thickness of metal layer is not large enough. A new configuration has been devised by them as given in fig 1.7 [25]. In this configuration as well, evanescent wave is needed to excite surface plasmons from a high refractive index glass prism at attenuated total reflection (ATR) condition. However, in this configuration, a thin film of metal layer (around 50 nm) is coated at the base of prism and brought in contact directly with the dielectric medium which has lower refractive index (such as air or some other dielectric sample). When a p-polarized light beam is incident on the prism-metal layer interface through the prism at an angle $\theta \geq$ ATR angle θ_{ATR}, the generation of evanescent wave takes place at the prism-metal layer interface. The configuration can be detailed by the given equation 1.12 [25].

$$\frac{\omega}{c}(\epsilon_p)^{1/2} \sin\theta_{res} = \frac{\omega}{c}(\frac{\epsilon_s \epsilon_m}{\epsilon_s + \epsilon_m})^{1/2} \tag{1.12}$$

1.4.2 Grating Coupling

In addition to prism coupling, there is an another approach that plays a vital role in the excitation of surface plasmons. It works on the principle of diffraction of light on diffraction gratings. In this coupling method, a light wave with a wave vector k falls on surface of gratings which is having grating depth of h and a grating period Λ shown in fig 1.8. The wave vector of diffracted light from the series of gratings can be written as [31]

$$k_m = k + mG \tag{1.13}$$

where m represents the order of diffraction and G denotes the grating vector. Normally the afore said wave vector is perpendicular to the grooves of grating and its magnitude $\propto \frac{1}{pitch \quad of \quad grating}$. It can be rewritten as [31]

$$G = \frac{2\pi}{\Lambda} z_0 \tag{1.14}$$

By using both the equation 1.13 and 1.14, the equation is altered as considering the k_{xm} is the incident wave [31]

$$k_{zm} = k_z + m\frac{2\pi}{\Lambda} \tag{1.15}$$

To form a good surface plasmon resonance condition, the diffracted wave propagation constant must be equal to surface plasmon (β^{SP}) [31]

$$\frac{2\pi}{\lambda} n_d \sin\theta + m\frac{2\pi}{\Lambda} = k_{zm} = \pm Re\{\beta^{SP}\} \tag{1.16}$$

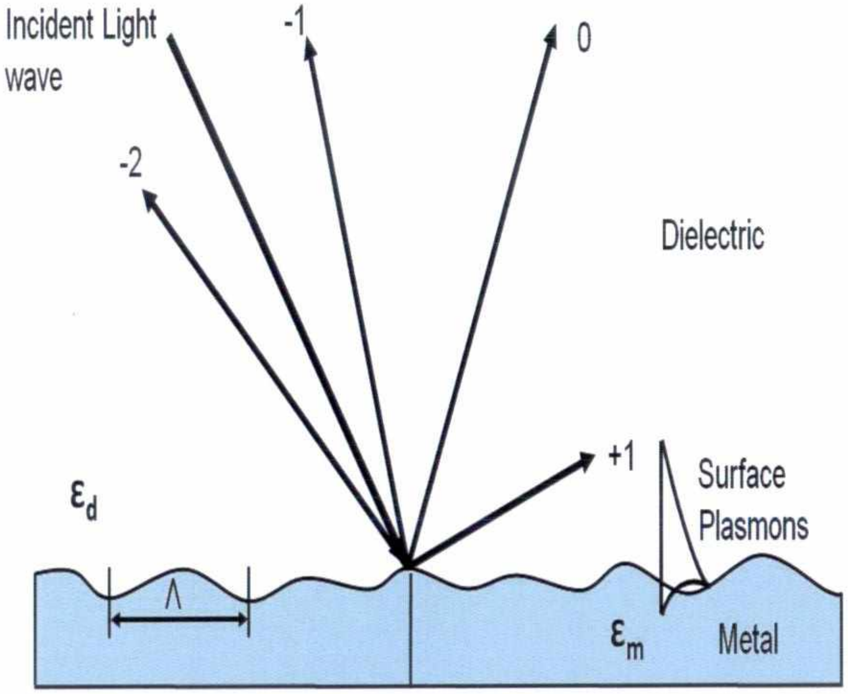

Figure 1.8: Excitation of surface plasmons by grating coupling

where as β^{SP} can be understood as [31]

$$\beta^{SP} = \beta^{SP_0} + \Delta\beta = \frac{\omega}{c}\sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}} + \Delta\beta \tag{1.17}$$

where β^{SP_0} is the surface plasmon propagation constant at metal-dielectric interface and $\Delta\beta$ denotes the grating. In terms of effective refractive index, the grating coupling condition can be expressed as [26]

$$n_d \sin\theta + m\frac{\lambda}{\Lambda} = \pm(Re\{\sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}}\} + \Delta n_{eff}^{SP} \tag{1.18}$$

where $\Delta n_{eff}^{SP} = \mathrm{Re}\{\frac{\Delta\beta\lambda}{2\pi}\}$. From eq. 1.18, it has been understood that to achieve the grating coupling condition various combinations of diffraction order, angle of incidence and grating pitch have been tried. The main feature of grating coupling is that reflectance dip totally depends upon the depth of gratings [32, 33]. However, grating coupling can be further identified as direct and indirect. In direct grating coupling, metal-dielectric interface came into direct contact of incident light from dielectric side [6], while indirect grating coupling involves the coupling of light through a prism or waveguide [34, 35].

1.4.3 Waveguide Coupling

Modes of dielectric waveguide can be used for excitation of Surface plasmon. Fig 1.9 illustrates the coupling method with the metal-dielectric waveguide in combination with dielectric waveguide. In this coupling method, a waveguide mode propagates along the waveguide and penetrates into metal layer region which further allows surface plasmon to couple at outer boundary of metal layer. For achieving better coupling, the propagation constant β_{WM} of the waveguide mode must be equal to the surface plasmon propagation constant β_{SP}. The detailed equation as follows [36]

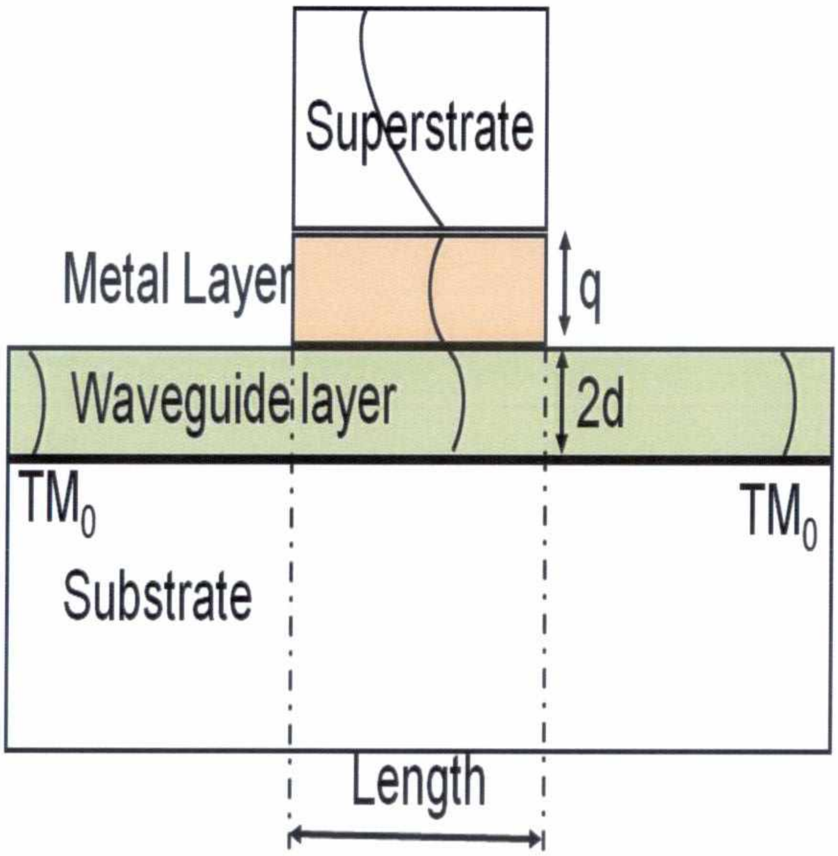

Figure 1.9: Surface plasmons excitation by waveguide mode

$$\beta_{WM} = Re\{\beta_{SP}\} \tag{1.19}$$

It may also be noted that waveguide modes are lesser dispersive than the surface plasmon modes as per above equation 1.19.

1.4.4 SPR Metals

Metals with permittivity in a negative real part and a positive imaginary part in near infra red and visible region which results in non zero imaginary propagation constant that allows the excitation of surface plasmons [37, 38]. The model which explain the motion of free electrons at resonance frequency is called as Drude free electron model for these metals. Using this model, the dielectric equation depending upon the frequency of electrons can be rewritten as [37]

$$\begin{aligned} \epsilon(\omega) &= 1 - \frac{\omega^2{}_p}{\omega^2 + \iota\Gamma\omega} \\ &= 1 - \frac{\omega^2{}_p}{\omega^2 + \Gamma^2} + \iota\frac{\omega^2{}_p\Gamma}{\omega(\omega^2 + \Gamma^2)} \end{aligned} \tag{1.20}$$

where ω_p is plasma frequency at which electron gas density oscillates. $\omega_p = \sqrt{\frac{ne^2}{\epsilon_0 m}}$ and Γ is the damping constant and can be written as $\Gamma = \frac{v_F}{l}$. The Drude model can be further extended using Lorentz method and taking into account interband transitions [37]

$$\begin{aligned} \epsilon(\omega) = \epsilon'(\omega) + \iota\epsilon''(\omega) &= \epsilon_\infty - \frac{\omega^2{}_p}{\omega^2 + \iota\Gamma\omega} \\ &= \epsilon_\infty - \frac{\omega^2{}_p}{\omega^2 + \Gamma^2} + \iota\frac{\omega^2{}_p\Gamma}{\omega(\omega^2 + \Gamma^2)} \end{aligned} \tag{1.21}$$

Gold (Au), Silver (Ag) are most often used as SPR metals because they exhibit a considerable amount of imaginary permittivity. Imaginary part of propagation further denotes the attenuation of surface plasmons. The relation between the attenuation and effective index can be written as [39, 40]

$$\begin{aligned} n_{eff} &= \frac{c}{\omega} Re\{\beta_{SP}\} \\ b &= \frac{0.2}{\ln 10} Im\{\beta_{SP}\} \end{aligned} \tag{1.22}$$

where Re {} and Im {} represents the real and imaginary part respectively and units of attenuation in $dBcm^{-1}$ if propagation constant β have unit in m^{-1}.

1.5 Surface Plasmon Resonance Sensor

In SPR senors, surface plasmons are excited at the metal-dielectric interface with respect to the change in refractive index which acts as measurand. The change in refractive index alters the propagation constant of surface plasmons. Accordingly, it changes the coupling condition between the surface plasmons and the incident light wave that includes a change in the characteristics of light wave [41]. Based on the characteristics of incident light wave, SPR sensors can be broadly classified as shown in fig 1.10

1. Angular Modulation
2. Intensity Modulation
3. Phase Modulation
4. Polarization Modulation
5. Wavelength Modulation

In angular modulation, the coupling strength between the surface plasmon wave and light is measured in terms of incident angle and treated as sensor output [42] with respect to refractive index change. In the same manner, for wavelength modulation, the strength of light and surface plasmons is observed in terms of multiple wavelengths which is to be considered as sensor output.

SPR sensors with intensity modulation, observes changes in the intensity of light which is measured as output whereas SPR sensors with phase modulation, faces change in the phase of light wave used as output considering a single incidence angle and wavelength. Apart from this, SPR sensors can also be identified as indirect or direct. In direct SPR sensors, refractive index directly modulate or change the light directly and indirect SPR sensors, a measurand or analyte modulates the quantity which in turn alters light characteristics. SPR based affinity biosensor are typical example of indirect SPR sensors.

In addition to this, following advantages can be achieved by adding gratings to metal-dielectric interface; firstly, it provide perfect momentum matching by which light can couple with surface plasmons [43, 44]; secondly it can act as perturbations to the surface plasmon propagation [39]. Along with this indirect coupling also uses grating at different angles for coupling at ATR [45, 46]. Our present work focuses to use the ATR method to couple the surface plasmon and use periodic grating to confound the light into it. In view of the above, it has been observed that miniaturization in photonic-circuits still remain a challenge due to the problem of phase matching between the surface plasmons and

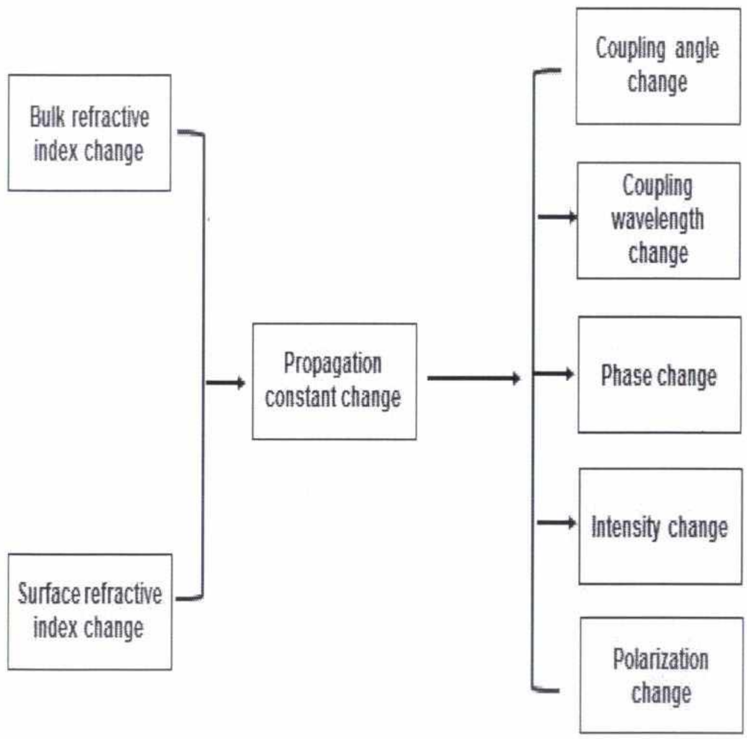

Figure 1.10: Classification of SPR Sensors

waveguide mode. The possible way to overcome this issue is to employ guided modes in given waveguide with the help of multilayer and gratings [47, 48]. Another silent feature of multilayer waveguide is that it facilitates the tunability in coupling as well as improves the performance of waveguide by altering the parameters of waveguide such as width of metal/dielectic layer etc.

1.5.1 Features of SPR Sensors

The performance of SPR sensors should be analysed with the help of mentioned below parameters. For achieving the best performance and better sensing of sensors, both sensitivity and detection accuracy (SNR) should be as high as possible.

1. **Sensitivity**

   Sensitivity of a SPR sensor is defined as how much shift will be occur in the resonance wavelength with a slight change in refractive index of a analyte or sensing layer. If the large shift is obtained, then sensitivity is high. Fig 1.11 describes relation between the reflectance and wavelength of the incident light beam for sensing layers having different refractive indices n_s and $n_s+\delta n_s$. Increase in refractive index by δn_s shifts the resonance wavelength by $\Delta\lambda_{res}$. The sensitivity of a SPR sensor is defined as pertaining to the wavelength interrogation method [24, 47]

$$S_n = \frac{\Delta\lambda_{res}}{\delta n_s}$$

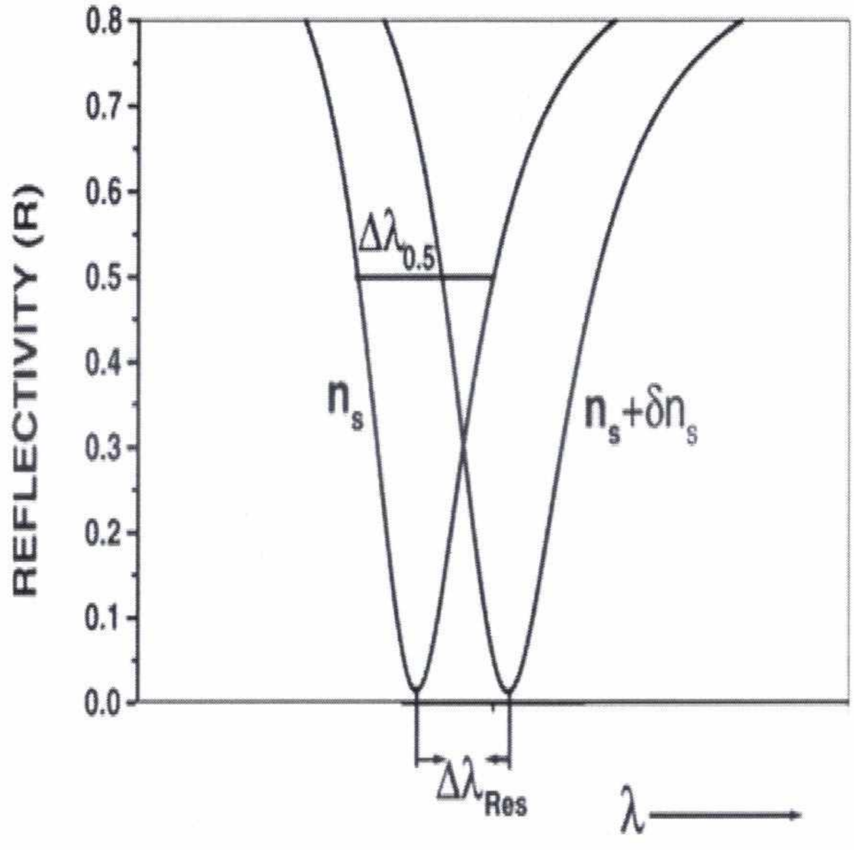

Figure 1.11: Illustration of SPR parameters with wavelength interrogation

2. **SNR (Signal to Noise Ratio) or Detection Accuracy**

The Signal to Noise Ratio (SNR) or detection accuracy of a SPR sensor is defined as how precisely and accurately the sensor can detect the light characteristics i.e. resonance wavelength and angle with respect to the refractive index of the analyte or sensing layer. The width of SPR curve is becoming narrower, the detection accuracy tends to increase. The resonance wavelength $\Delta\lambda_{res}$ get shifted with refractive index change of the analyte or sensing layer n_s by δn_s. $\Delta\lambda_{0.5}$ is the angular width of the resonance curve at half transmittance/reflectance for analyte or sensing layer refractive index n_s [24]. Therefore, if $\Delta\lambda_{0.5}$ is the angular width of the SPR response curve at 50% transmittance/reflectance, the signal to noise ratio or detection accuracy of the sensor can be considered to be inversely proportional to $\Delta\lambda_{0.5}$ as shown in fig 1.11. The SNR or detection accuracy of the SPR sensor with wavelength interrogation method is, thus, defined as [25, 49]

$$SNR = \frac{\Delta\lambda_{res}}{\Delta\lambda_{0.5}}$$

Actual signal to noise ratio (SNR) or detection accuracy of the real SPR sensing system critically depends on how well real instruments can be used for measuring the signals.

1.5.2 Surface Plasmon Resonance Affinity Biosensor

SPR based affinity biosensors are sensing devices which are having a sensing layer of biorecognition material that help to identify and able to amalgamate with a selected analyte. Further, it consists of a surface plasmon resonance transducer which renders the binding signal into an output optical signal. The biorecognition materials are restrained in the adjacency of metal film surface that support surface plasmons phenomena. A liquid sample that contains analyte molecules bind with biorecognition materials when come in contact with the SPR based affinity sensor. Accordingly, an increment in the refractive index at the SPR based biosensor surface is observed, which is measured optically[50, 51].

Sensitive, fast and specific detection of molecular bio-markers indicating pathogenic processes, biologic processes to a therapeutic intervention presents an important goal for modern bioanalytics.

Surface plasmon resonance is surface oriented method that is showing a great potential for affinity biosensor and also allow the real time analysis of bio-specific quantities without using of labeled molecules [36]. The use of SPR in optical waveguide offers numerous features i.e. to control the optical path and efficient control of light properties etc.. In context to that use of gratings and multilayer waveguides have merits of robustness, compatibility of interfacing with external devices etc. [48, 52].

Chapter 2

Literature Survey

2.1 Introduction

In optical sensing systems, the excitation of surface plasmons occurs optically and is detected in the form of light wave. The characteristics of light further processed to yield an output. SPR affinity biosensors includes a biorecognition element coated over a metal layer that interacts with the target molecules in the sample (also called analyte). In view of the above, surface plasmon resonance based sensing have numerous advantages. The potential of surface plasmon resonance was first recognized with thin films and monitoring of light at metal-dielectric interfaces in late seventies.

As earlier discussed in chapter 1, many techniques are available in the field of sensing applications. But when it comes to chemical and biological sensing, it is very important to detect the analyte precisely and accurately in this respect, SPR based biosensor show a promising results in the field of food quality and safety, environmental monitoring and medical diagnostics etc and meet all the expectations of current scenario. Still, there are huge chances of improvement to explore new designs, configurations and methods that enhance the sensitivity and detection accuracy of SPR based biosensor. In continuation to this portable reliable biosensors with improved sensing range are observed. In this chapter, a comprehensive literature review of different multilayer waveguides along with combinations of different metals is presented. The use of gratings with multilayer in the study showed different design and structures with high performance w.r.t to sensitivity, transmission of light and detection accuracy.

2.2 MDM Waveguides

In last eighties, M. Matsumoto et al. [53] presented theoretical analysis of radiation characteristics of a slab of dielectric covered with layers of thick metal using boundary integral method. By numerical calculation, it was found that TM modes have large leakage constant than the fundamental TE mode for abovesaid geometry. While Prade et al. [54] derived all guided modes in heterostructures (i.e. sandwiched two dielectric media with negative dielectric constants). All waveguides was considered as lossless.

E. Anemogiannis et al. [55] presented a numerical method for determination of real and complex propagation constant for any lossy and lossless waveguide structure (dielectric and metal).

In lossy waveguide, leaky waves and guided modes for multilayer waveguides were calculated using argument principle method and thin film transfer matrix. Argument principle method based on zeroes have been applied to multilayer lossless, lossy and leaky waveguides. Different types of waveguides have different refractive index profile, it can be further explained by APR method using this equation [55]

$$h(x) = \begin{cases} \sqrt{n^2{}_S + 2\triangle n_S exp\frac{x}{\alpha}} & x < 0 \\ n_C & x > 0 \end{cases}$$

where $\triangle$ and α are design constants and n_C, n_s are the cover and substrate indexes and x = 0 relates to the substrate-cover boundary.

G W Forbes et al. [56] presented a new direction in the optical fields on basis of ray theory. They build a new framework for the propagation of light at the interfaces through reflection, refraction and smooth media. The impact of surface plasmon across the bends and curves is very important factor with respect of transmittance, reflectance and energy coefficients. To exercise this advantage, Hasegawa et al. [57] analysed theoretically propagation of surface plasmons along a finite bend of metallic structure. It was found that propagation around non-planar interface have lower losses than the planar or flat surfaces. Maximum transmission was achieved by decreasing the bending radius of metallic corner. Thus, it put forward a new light on propagation mechanisms of surface plasmons for extra transmission which further helped for new designs and optimization of geometry.

Schmid et al. [9] demonstrated the use of subwavelength gratings patterns to obtain the highest reflectivity by various simulations. Experimental results showed that using triangular gratings pattern, reflectivity below 1% was achieved at a wavelength of 1.55

μm. Around 2.0% to 2.4% value of reflectivity was also investigated for TE and TM modes on silicon-on-insulator waveguides.

N.N. Feng et al. [58] presented a subwavelength structure with metal slot to enhance the surface plasmon propagation with a high index material. It was also revealed from the above study that metal thickness have to be scaled very carefully because beyond this, radiation modes align with leaky wave which inturn leak out of guiding region. By using SiO_2 material in the slot, propagation losses got reduced to $\sim 0.14dB/\mu m$ against propagation length of $\sim 50\mu m$.

Dependency of polarization on square and triangular gratings pattern have also been studied. A. Sellai et al. [59] theoretically optimized the MDM geometry by tuning the metal layer and grating depth. It was observed that by decreasing the thickness of metal layer, coupling between the modes has been increased. A trade off between longer propagation distance and highly confined modes were also analyzed by estimating penetration depths of SPP and prorogation lengths in three metals (Aluminium, Gold and Silver) respectively and dielectric region.

Salvador et al. [60] proposed a hybrid plasmonic waveguide based on SOI platform which showed strong light confinement in the diffraction limit and low propagation losses. This hybrid plasmonic waveguide geometry has been theoretically and numerically analyzed in terms of sensing and some other valuable parameters. Some design parameters and design criterion have also been studied to analyze the different types of modes (TE or TM) taking the high contrast materials. An overview of performance of several type of dielectric and plasmonic waveguides have been presented.

Prism based system was lagging in terms of sensitivity using diffraction gratings and angular interrogation method. To improvise the sensitivity with gratings Cai et al. [61] proposed double dip method to improve the sensitivity by $237^0/RIU$. The effect of using two different plasmonic materials for guided mode dispersion has been analysed in comparison to the same plasmonic material.

B pakov et al. [62] presented theoretical analysis of surface plasmon resonance optical fiber sensor based on Bragg gratings using coupled wave theory. Further investigations revealed that coupling of fundamental mode to cladding mixed modes is associated with the narrow transmission dips. A resolution of refractive index for the above said sensor was found to be $2X10^{-6}$ RIU. Overall performance of double dip method was been observed to be better if used with rectangular gratings. However, dispersion characteristics under MDM structure were still not investigated.

Single layer interface lacked some properties, to overcome this; Chen et al. [63] theoretically investigated Metal-Dielectric-Metal geometry to understand the surface plasmons coupling. It also improved the frequency between the plasmon gap and tuning between their densities. It was experimentally observed that using different dielectric thickness (180-220 nm) with a symmetric metal layer of thickness 300 nm have high resonant energies of SPP.

Bhatia et al. [64] experimentally presented a comparison of n-type and p-type silicon over SPR based optical fiber sensor. It was also studied that sensitivity of n-type silicon using silver metal layer is $\sim$ 1.39 times higher than p-type. While using gold metal layer n-type silicon sensitivity was also $\sim$ 1.50 higher than p-type silicon. Based on the above study, it was also found that silicon charge carriers played an important role in the sensitivity as it mainly alter the propagation constant and present field in the analyte region.

C. Athanasopoulos et al. [65] presented simulation of propagation of SPP using FEM technique. It showed that the presence of dielectric not only compensates the metal absorption losses but also enhanced the surface plasmon propagation.

Katyal and Soni [66] worked on dielectric layer thickness and composition of core and metal layer to know the impact on resonance wavelength. It was observed that bimetallic layered structure support higher senstivity, tunable plasmon resonance wavelengths and a high RIS factor of 510 nm/RIU for Al-Air-Au and 470 nm/RIU for Ag-Air-Au. The specified advantage as discussed above made them attractive for medical and bio-chemical sensing.

Yang et al. [67] numerically investigated decay and propagation properties of symmetric MDM waveguide which consists of Au/Al_2O_3/Au metal layers. It was found that the propagation length totally depends on Al_2O_3 layer thickness. Maximum propagation length achieved during excitation of SPP was 0.608 μm with a thickness of 100 nm of Al_2O_3 layer. Dipole and the interface between Au/Al_2O_3 will be considered to influence parameter for decay properties. Decay lengths obtained at electric and magnetic field are 19 nm and 24 nm. Obtained results imply that high performance can be achieved by adjusting the thickness and width of dielectric layer.

Further, Verma et al. [68] investigated the various parameters i.e. detection accuracy, sensitivity & quality factor of SPR based biosensor taking air gap as a dielectric. Sensors get optimized by adjusting the layer thickness of silver metal and air gap. It was reported that said biosensor have 2.35 times sensitivity than the biosensor without air gap. Various effects, i.e. chemical potential and temperature were also analyzed with graphene in combination of SPR biosensor with airgap.

In addition to these, some work pertaining to the field of MDM waveguides are tabulated in table 2.1.

Table 2.1: Summary of outcomes of various investigators in the field of MDM waveguides

Investigator [Year]	**Material Used**	**Parameters Investigated**	**Outcomes**
S Aldawsari et al. [2017] [69]	SiO_2	Guided Modes, Dielectric Thickness	Theoretically investigated guided modes in five layer MDM waveguides. Proposed structure support different types of MDM modes at a variable thickness of the dielectric. Geometrical parameters and refractive indices can control the performance of waveguide.
Yin Huang et al.[2017] [70]	Silver and Gold	RI senstivity, Sensing length	3.5 to 3.9 times senstivity enhancement in RI senstivity apart from this, 2 to 3 times reduction in sensing length
Zhihui He et al. [2017] [71]	Silver, SiO_2	Transmission Characteristics, Figure of Merit	Proposed coating method to avoid oxidation and keep good sensing performance and also discussed the decaying electric field at a thickness of 8 nm SiO_2 and Ag_2O layer
S Elbialy et al. [2017] [72]	Silver, SiO_2	Transmission	Proposed geometry satisfies insertion loss ≈ 0 dB for desired output channel and also rejected a transmission band at wavelength of 1510-1585 nm.
M H Keleshtery et al. [2017] [73]	Gold, Polymethyl methacrylate	Plasmonic modes	Proposed geometry slow down the velocity of plasmonic waveguides using waveguide bends
Z Huang et al. [2017] [74]	Gold and Silver	Excitation efficiency, Extinction ratio	Investigation of metal-insulator-metal (MIM) waveguide and plasmon on metal-insulator (MI) interface for parallel coupling has been done. Realisation of new unidirectional plasmon generator has been done. High extinction ratio as 1:170 with excitation efficiency of 78% has been achieved.
Jing Guo [2014] [75]	Gold, Polymethyl methacrylate	Resonance wavelength	Controlling of resonance wavelength by altering the length of cavity. Multiple peak plasmons has been investigated using cascaded multiple activities

2.3 High Performance Sensor

Generally, attenuated total reflection method is being employed for surface plasmons excitation. To achieve this, Nylander et al. [76] pioneered a new and simple method for sensing purpose. Having the advantage of simplicity, it can be further applied to biochemical sensing and even for thin film characterization.

Qazwini et al. [77] investigated SPR based optical fiber using FDTD method. The effect of thickness of metal layer & amount of cladding has been analysed and optimized for a good transmission dip as well as higher sensitivity and narrower dip. A proper combination of gold thickness (40 to 60 nm) and the optimized cladding (400 to 500 nm) is much needed for a good optical biosensor in aqueous environments.

In continuation of this, Cullen et al. [78] improvised the sensing by introducing the use of diffraction gratings. The gold coated based grating technique used to detect the immuno-complex formation in human and sheep antiserum. In 1980's a new configuration was proposed with gold coated diffraction gratings with normal incidence. According to this, symmetry of structure has been achieved which allowed to generate two SPR dips for each grating.

Based on this method, a grating based angular modulated SPR sensor was reported by Dostalek et al. [79] with high number of sensing channels that allowed high-throughput screening applications.

M. Jory et al. [80] used the AOTF to enhance the intensity of reflected beam with respect to the applied input wavelength. By optimizing the AOTF filter, proposed sensing geometry achieved a precision of 0.0005 nm. Further, by adding a chemical active layer to the aforesaid geometry, detection of concentration of 0.01 ppm of NO_2 in N_2 was possible.

C.R. Lawrence et al. [81] emphasized about the use of gratings in place of prism and also listed some advantage i.e. low cost & easy fabrication.

Besides comparison of diffraction gratings and prism based sensors, Homola et al. [82] presented a theoretical analysis for the sensitivity comparison of diffraction gratings and ATR based prism couplers based on angular and wavelength interrogation method. The analysis discovered that wavelength interrogation based prism couplers have high sensitivity than the gratings. While in angular interrogation method sensitivity depends upon the diffraction order and have same resemblance as prism couplers. Usually SPR measurements involve mainly gold and silver as metal layer in SPR, since every metal has its own characteristics as gold has a higher shift with respect to change in the refractive index while silver owns a narrower resonance curve and results in higher SNR, on the other hand it has poor chemical stability. To overcome this a thin or dense cover of gold layer/some other metal layer can be a good option.

Counting the advantages of both the metal layers, Zynio et al. [83] suggested a new structure of bimetallic layer taking gold as outer layer to overcome the chemical stability. This structure displayed good shift of wavelength resonance w.r.t change in refractive index. It is worth mentioning that increment in the SNR due to bimetallic layer allowed to use the proposed geometry for small molecules binding. Thus geometry can be further extended to biology, medicine and pharmacology applications.

Cao and Nahata et al. [84] demonstrated enhanced transmission of thin metal films using periodic subwavelength arrays. Accordingly, aperture shapes along with aspect ratio, shapes were also explained to meet the extra ordinary transmission.

In the same manner, A. K. Sharma et al. [47] provided theoretical analysis of SNR and sensitivity of bimetallic fibre optic SPR sensor. Different bimetallic ratios of gold and silver layer were studied for comparison of sensitivity and SNR. It was observed that for bimetallic layer thickness (50 nm) in ratio of (3:1)[silver to gold], signal to noise ratio is totally depends upon the NA of fiber for a sensing length of 10 mm. It was also evident that if launching angles are brought near to the critical angle, then the SPR dip gradually decreases. From the above said study, effects of numerous design parameters i.e. metal layer thickness, metal layer ratio, Numerical Aperture (NA), launching angle alters the performance of SPR fibre optic sensor. It was also understood that by using meridional ray, the performance of said sensor can be enhanced experimentally.

Xiao et al. [85] theoretically studied the enhanced transmission with subwavelength hole arrays using a thin gold film. Obtained resonance peak was too broad and shift was not fairly pronounced. Enhanced transmission with subwavelength arrays opened new ways for SPR based optical sensing.

Allosp et al. [86] demonstrated the use of gratings in the single and multilayered thin films for a D - shaped SPR waveguide. Single layered structure got fabricated with germanium while multilayer compromised with germanium, silica & silver. Both the SPR waveguides attained sensitivity of 6790 nm/RIU and 90 nm/RIU against a refractive index range of 1.33 to 1.36.

Gupta et al. [49] addressed various designs such as U-shaped, side polished and tapered to enhance the performance of fiber optic sensors. They also reported the advantages of bimetallic coatings, choice of metals and addition of dopants over the conventional SPR sensors in terms of sensitivity.

Anuj Sharma et al. [87] proposed a theoretical model of chalcogenide glass and SPR based gas sensor. The SPR sensor consist of metal layer of Gold (Au) - Silver (Ag) alloy along with angular interrogation method. Sensor's performance was studied in relation of size and ration of alloy nanoparticle. It was observed that with increase in nanoparticle size and ration of silver in alloy sensor's performance got improved.

Hu et al. [88] investigated grating coupled bi-metallic surface plasmon resonance sensor to achieve high performance using angular interrogation method. To overcome the chemical instability of aluminium (Al), a thin film of gold (Au) in combination of gratings has been deposited. Further, presence of aluminium exhibit sharper resonance dip and enhanced detection accuracy. By simulating the above said geometry, sensor achieved senstivity of $182.7^0/RIU$ and FWHM of 0.93^0. Apart from this, good quality factor of 201 RIU^{-1} was also achieved in association with -1 diffraction order of metallic gratings.

Sarika Singh et al. [89] presented a theoretical model of miniaturized LED based SPR fiber optic sensor. Performance of LED sensor has been compared with the focusing and collimated source light sensor. This study revealed the advantage of LED based sensor in terms of miniaturization, low cost and compactness. It was also reported that sensitivity of this proposed geometry should be increased for a larger core diameter and higher NA of fiber along with small sensing region.

Based on the findings of multilayers, Srivastva et al. [48] proposed a bimetallic layer SPR waveguide sensor which compromised of periodic gold and aluminium layer. By adding the advantage of aluminium (Al), a better performance has been achieved using couple mode theory. At a wavelength region of $\lambda = 1.50\ \mu m$, senstivity of around ~ 5340 $nm - RIU^{-1}$ along with detection accuracy of $\sim 130\mu m^{-1}$ has been retained.

Tu et al. [90] investigated the alloy of gold and silver as an active elements for optic fiber sensing systems. Alloys studied in detail for different combinations i.e. 25% gold + 75% silver or 25% silver and 75% gold. The experimental results showed that alloy group with 75% silver and 25% gold achieved better senstivity $\sim$ 611 nm/RIU and vice-versa. Further, it has also been studied that design process can also tailor the sensitivity of SPR based optical fiber sensor.

In addition to that, Li et al. [91] proposed a bi-compatible sensing coating with Frensel diffraction for detection of pH. Experimental results revealed that said sensor has fast response, good reproducibility and repeatability. The achieved amount of senstivity was 0.018 RIU/pH with a good resolution of 0.01 pH unit against pH concentration of 5.87 - 10.55. By applying the concept of multichannel, the effect of light source, propagation losses and the influence of environment got eliminated.

Table 2.2: Performance Parameters of various optical sensors

Sensor type	Detection RI range	Senstivity	Ref.
SPR MMF, Au coating	~1.33 - 1.37	~ $2X10^{-4}$ RIU	[92]
SPR cladding removed, gold coating	~1.3335 - 1.4018	~ 1600-3000 nm/RIU	[93]
Long period grating with gold coating	~ 1.329 - 1.340	~ 1100 nm/RIU	[94]
Fiber Bragg tilted grating with gold coating	~ 1.3-1.38	~ 3365 nm/RIU	[95]
Multimode tapered fiber with gold coating	~ 1.333 - 1.343	~ 2750-15000 nm/RIU	[25]
Multimode fiber with silver and SiO layer	~ 1.3365, ~1.4126	~ 3800 nm/RIU	[96]
Optical fiber D shaped with germanium, silicon dioxide and gold, silver	~ 1.0-1.15, ~ 1.333-1.39	~ 90-800 nm, ~ 1200-1400 nm	[97]
Grating coupled multilayer with Al and Au coating	~ 1.32-1.37	~ 187.2^0/RIU	[88]
Bimetallic sensor with period multilayer with Al and Au coating	~ 1.360-1.361	~ 5340 nm/RIU	[48]

2.4 SPR based biosensor

Whole world is concerned about the early cancer diagnosis as it is still localized and curable [98]. Thus, changes in present detection method can improve patient outcomes. The above discussed methods can be used for early detection with a high degree of accuracy which further allows to distinguish healthy individuals from cancerous cells. This can help to detect the aforesaid disease before it proceeds to an advanced stage [99]. Early cancer diagnosis research put to identify specific biological markers to distinguish between healthy samples and cancer samples [100, 101, 102]. Present scenario has marked the importance of detection of small differences in the protein concentrations for cancer cases and healthy individuals . Need of the hour is to have non-invasive methods to detect cancer biomarkers [103]. Protein arrays are increasingly being used as a diagnostic tool in clinical applications [104].

Research on affinity biosensors is primarily focused on developing reliable chemistries and methods to detect multiple analytes simultaneously. Better sensitivity and false detections are important considerations when designing a sensor. Surface plasmon resonance (SPR) based sensors is one of the latest technique that combines methodology of SPR with spatially resolved measurement [105, 106, 107]. SPR based bio-sensors make use of real-time, spatially resolved monitoring of bio-molecular interactions on a two-dimensional detector array, allowing for arrays of interactions to be examined for kinetics [108], as well as end-point assays [109]. Many other works have demonstrated the use of enzymatic amplification to improve sensor response [110]. Maheswaran et.al [111] reported that mutations in the epidermal growth factor receptor (EGFR) gene can be detected in CTCs isolated from lung cancer patients.

Furthermore, De Pas et al. [112] observed that repeated measurements of EGFR for lung cancer patients is mandatory to better the results of chemotherapy. SPR based fiber optic sensors emerged as an indispensable tool used for biological and chemical applications. Use of bimetallic layer and gratings added extra features to said sensors and improved the detection accuracy and sensitivity.

A. Hassani et al. [113] proposed microstructured SPR based optical fiber sensor with microfluidics. Phase matching between the core guided and plasmonic modes is very sensitive to change in the analyte refractive index. Phase matching can also be achieved by putting the hollow structure into the fiber core to lower the effective mode index. Refractive index change of 10^{-4} of microfluid as analyte can easily detect about 1% change in transmitted light intensity.

A.K. Sharma et al. [24] reviewed all the techniques and mechanisms of SPR sensing for physical, chemical and bio-chemical parameters. Despite this, advancement in the existing mechanisms and new different models in the said area has also been discussed.

In continuation of this Rajneesh K Verma et al. [25] proposed a theoretical model of SPR based fiber optic sensor with tapered regions. It was studied that taper ratio between 1.5 and 2.0 showed the best performance in terms of sensitivity and detection accuracy.

Rajan et al. [114] reported fabrication of SPR based fiber optic sensor for the detection of pesticide using competitive binding. The characterization of the said sensor has been done using spectral interrogation method. The sensitivity, stability and detection accuracy were also studied with respect to concentration of chlorphyrifos. Now a days biosensor technology emerged as a fast, accurate and reliable detection method for medical diagnostic and even some biological applications.

A new method has been introduced by Choi et al. [115] in the field of biosensing which further improved the selectivity. A new SPR based protein sensor was reported for the selective, real time detection of protein using Vroman effect.

Using this method, Choi et al. [115] bypass the dependency of bio-receptors and easier the complex and time consuming process of detection. J Ladd et al. [116] compared SPR imaging sensor with conventional spectroscopy sensor based SPR sensor. This sensor was presented for detection of two cancer biomarkers i.e. ALCAM and TAGLN2. Limit of detection obtained using SAM layer for ALCAM (CD 166) & transgelin-2 (TAGLN2) was 6 ng/mL and 3 ng/mL respectively.

Allosp et al. [97] fabricated D-shaped surface plasmon resonance sensor with multilayer coatings in combination of gratings. Thin films in multilayer fashion consisted of semiconductor (germanium) and dielectric (silicon dioxide) materials, followed by different metals (i.e. gold, silver and platinum). The obtained sensitivity using silver and platinum was 90 nm/RIU and 700 nm/RIU with an efficiency of 40 dB in air while gold metal showed spectral sensitivity of 4000 nm/RIU over a refractive range of 1.33-1.39.

Bohunicky et al. [50] reviewed the current scenario of biosensor as a diagnostic tool and also summarised the present difficulties of early detection of cancer & further expansion of this technology toward the POC testing devices.

Altintas et al. [117]developed an SPR based immunoassay biosensor for the detection of Carcinoembryonic antigen (CEA). A detection limit of 3 ng ml^{-1} for CEA concentration with the help of assay design was achieved.

Grinevich et al. [118] studied the imperfection in the tin oxide nano composite films in wavelength range of 400-1600 nm. Their main aim of work was to reveal absorption in the said films. In context of this, polarization difference $\rho = {R_s}^2 - {R_p}^2$ showed different behaviour for continuous and cluster films of tin oxide.

Sarika et al. [119] reported the fabrication of surface plasmon resonance based fiber optic sensor for the detection of pH in aqueous liquid. Said fiber optic sensor consisted of three layers of silicon, silver and ph sensitive hydrogel layer and used the wavelength interrogation method in the visible wavelength region. The environmental temperature $(16-28)^0C$ has negligible influence on the performance of sensor. As the concentration of pH increased, blue shift in resonance wavelength has been observed. Experimental results showed better stability, short response time (about 1 min), remarkable sensitivity and highest detection accuracy with respect to the measurement of pH. The above sensor also carried the following advantages i.e. reusability, low cost, miniaturization and remote sensing.

Bhatia et al. [5] fabricated three layered (silver, silicon & enzyme layer) surface plasmon resonance based fiber optic sensor structure over a length of 1 cm for the detection of urea in the blood. The reported sensor should be operated in 0-160 mM close to range of medical sciences. The characterization of the said sensor has been done using wavelength interrogation method. Experimental results showed that senstivity became zero beyond 180 nM concentration of urea while detection accuracy was independent of urea concentration.

J. Baniukevic et al. [120] developed a simple, robust and indirect method for the detection of leukemia virus antigen gp51 using surface enhanced raman scattering (SERS). The observed LOQ and LOD for above said sensor using magnetic gold nanoparticle were 3.14 μgmL^{-1} and 0.95 μgmL^{-1}. N. Ghosh et al. [121] reported SPR based waveguide sensor for the detection of protective antigen (PA) found in human serum. An assay has been attached to the gold coated carboxymethyldextran chip which can detect 1 pg/ML purified PA. While human serum samples contain 10 pg/ML of PA for better and early detection and also serve as diagnostic biomarker for *B. antharcis* infection. For achieving such optimization, affinity interactions of kinetic parameters such as equilibrium constant (K_D) and maximum binding of analyte (B_{max}) was calculated using kinetic evaluation software. Effect of temperature on structure and antigen antibody interaction has been studied. It was found that for smooth operation of sensor chip, 25^oC was the optimum temperature while beyond 25^oC, the maximum downward variation in SPR angle had been observed.

PENG et al. [122] presented multi-alternating metal layered SPR based fiber optic sensor for biological or biomedical applications.

The effect of different metal layers has been investigated in light of resonance wavelength (400 nm to 1200 nm). They also numerically simulated the effect of thickness of metal layer and no. of alternating layers for attaining the highest sensitivity. Further results showed that multilayer have a better detecting range as compared to the single layered optical fiber sensor in the field of biological analysis.

Chau et al. [123] investigated the use of titanium oxide for surface plasmon using silver nanobeds. FEM method was used numerically for a dielectric constant of silver nanobeds from 1.7689 - 11.56 keeping the incident angle at a range of 30^0 - 75^0. It was observed that said device can be fabricated easily as it has a large area photocatalytic material.

Quero et al. [124] developed a new method i.e. LPG based fiber optic nano-optrode for the detection of thyroid cancer. A reflection type biosensor having a coating of atactic polystyrene (aPS) which further allowed for label free detection of human Thyroglobulin (TG). Analyte binding performed with ELISA assay technique for a concentration of 0-4 ng/mL. This method also wash out the needle based biopsies. Researchers are continuously working to improve the efficiency and accuracy of biosensing. Table 2.3 shows a brief review of biosensing modifications.

Table 2.3: Summary of outcomes of various investigators in the field of Biosensing

Investigator [Year]	**Material Used**	**Parameters Investigated**	**Outcomes**
F A Geiss et al. [2017] [125]	Aluminium	Senstivity and Figure of Merit	Crossed relief aluminium grating has been investigated for detection of protein (OBP14). Wavelength interrogation method has been employed for diffraction coupling.
A Thakur et al.[2017] [126]	Gold	Limit of detection, Dynamic range	Depending upon concentration, method for detecting exosomes and microvesicles has been investigated. A LoD of 0.194 μg/ml has been attained using gold nanoislands
A Gao et al. [2017] [127]	Silicon	Early detection, senstivity	Lung cancer biomarkers CEA and miRNA-126 has been detected using silver nanowires. It can also provide the fast and reproducible sensing for early detection of lung cancer.

to be cont'd on next page

Table 2.3: Summary of outcomes of various investigators in the field of Biosensing (Cont.)

Investigator [Year]	**Material Used**	**Parameters Investigated**	**Outcomes**
C Ribaut et al. [2017] [128]	Gold	Senstivity	Optical fiber immunosensor for the detection of lung cancer biomarker i.e. cytokeratin 17 (CY17) has been developed. Experimental results concluded that sensor have a good response towards the target protein
G Selvolini et al. [2017] [129]	Gold and Silver	Senstivity and detection accuracy	Molecular imprinted polymer based sensor has been reviewed for different lung cancer biomarkers. As certain biomarkers have the potential to provide a diagnosis pattern.
M A Tabrizi [2017] [130]	Gold and Graphene	Detection and LoD	A novel electrochemical Bi-aptasensor using gold and graphene has been proposed. A DPV technique has also been employed for the detection of VEGF and CYC in human serum sample.
T Liao et al. [2017] [131]	Gold	Senstivity and specificity	Phosphorodiamidate morpholino oligos (PMO)-functionalized nanochannel biosensor for label-free detection of microRNAs (miRNAs) with ultrasensitivity and high sequence specificity has been demonstrated. Apart from this, this sensor attained a limit of detection of 1fM in PBS and 10fM in serum sample.
C S Huertas et al. [2017]	Si_3N_4	Senstivity and Specificity	A nanophotonic biosensor employing direct splicing of Fas gene has been reported. This biosensor has proven very specific to detection and having minimum detection biases.

2.5 Gaps Identified in Present Study

1. According to the literature survey, it has been observed that wavelength and resonance angle are said to be the key parameters which indirectly influence the sensitivity and detection of SPR sensor. Moreover, most of the arguments are advocating for depositing a single layer of gold or either silver metal on the glass surface for a good design of probe of SPR sensor.
2. Above literature also radiate that many SPR metals lack chemical stability due to their oxidation whereas some metals have different shortcomings such as they are more expensive and have less sensitivity as compared to silver etc. The oxidation of silver metal is major concern as it is easily exposed to water and air, due to which reproducible result can be affected.
3. Geometrical parameters like width and height of metal layers and grating effect light propagation in waveguide and also effect the SPW propagation along the dielectric layer.
4. Further, multilayer geometry overcome the limited capability i.e. oxidation problem, detection accuracy which in turn degrades the sensitivity slightly.
5. Transmission efficiency and propagation length also become the imperative factors that are presented in SPR waveguide.

2.6 Problem Formulation

The large scale commercialisation of optical sensors is being limited to some constraints. Some important constraints are listed as high cost of sensor and type of transducer/signal processing systems. In the current scenario, cost effective and eco-friendly sensing equipment would benefit the field of public health and bio-chemical.

In most of the SPR based conventional sensors that are based on prism as the primary waveguide require Krestchmann configuration with which access to the guided/waveguide modes to detect the fluctuations in the ambient environment becomes possible. This interaction with waveguide mode and guided modes can be achieved directly by inserting gratings or indirectly by coupling to a guiding layer which can often interact with the analyte or medium.

Existing surface plasmon resonance based sensors are based on the surface plasmons interactions between metal and dielectric layer, because a normal SPR sensor either conventional or optical is directly insensitive to variation of refractive index, the buffer layer between the metal and analyte layer must be chosen carefully. Fabrication of gratings is time consuming and require a high degree of control. The disadvantages of inscribing gratings is of cross sensitivity. Even durability of SPR based sensors will be slightly reduced in comparison to other type of optical sensors. The above said disadvantages limit the SPR based sensors enormously. Apart from this, mutilayer SPR sensor is based on gratings and have huge potential to provide better sensing platform for refractive index [97].

SPR sensors couple the guided mode to propagation constant which further cause a resonance condition that cause attenuation in the transmission peaks in spectrum. SPR sensors have higher sensitivity to the variation in refractive index according to the present media i.e. chemical/biological analyte etc. without diminishing the other properties of used materials. As they have a stronger resonance condition depending on refractive index of metals and propagation constant of input light. At present, cancer detection using invasive technique in human serum is highly an attractive choice. In the current scenario, death rate due to lung cancer is on continuous increase and the air pollution is continuous to be a pressing issue, there are many other existing reasons which have forced us to design a tool/sensors based on SPR for early detection of lung cancer. Various sensing methods based on SPR waveguide schemes have been studied to develop the best optical SPR sensor for lung cancer detection. Several SPR based sensors using different metals and dielectric materials with distinct sensitivities & detection accuracy as well as quality parameters have been investigated in the above section.

Multilayer offers more variety in SPR design in combination with gratings and performance characteristics as compared to mono-layer SPR waveguide sensor, since the spectral response may be further tuned by metal thickness, grating period, width of gratings and numerical aperture. In view of the above, multilayer concept with wave interrogation method have the merit of good coupling with input light sources as discussed above and other optical components due to the subtle nature of SPR metals and inscribed gratings in the core of waveguide yield to lower cost sensing systems. Therefore, multilayer concept in combination with gratings and wave interrogation method have already received attention in recent years.

A low cost and effective SPR waveguide sensor based on multilayer concept and gratings can be very useful. Generally reliability associated with SPR sensor is due to its reusable factor and usefulness to chemical as well as biological applications. Many disadvantages associated with the SPR sensor can be overcome by using simple light source in combination with grating period and pitch. A multilayered and grating based SPR sensing scheme can be used for high senstivity, better detection accuracy and good quality applications.

2.7 Objectives

The following research objectives are formulated:

1. To analyze the different parameters of Surface Plasmon Resonance (SPR) waveguide for sensitivity enhancement.
2. To examine the performance of different materials for Surface Plasmon Resonance (SPR) waveguide.
3. To investigate coupled Surface Plasmon Resonance (SPR) waveguide for sensing applications.

2.8 Major Contribution of Thesis

As outlined in the contribution section, the main objective of this research work was to find out a way to outline the limitations of surface plasmon resonance waveguide sensor as discussed above. Main aim of the thesis was to develop and optimise the SPR waveguide sensor based on multilayer & gratings embedded on it and also to achieve the superior performance when compared to existing and conventional sensing techniques. The performance of SPR waveguide sensor was measured in terms of sensitivity and detection accuracy with respect to the refractive index change. The major contribution of the current thesis are listed below, in light of the /objective of this research work.

The optical properties of SPR metals or metals which has negative refractive index has been investigated in single and multilayer concept in symmetric and non-symmetric Metal - Dielectric - Metal structure. Possibility of extra order transmission with the help of a slot in MDM waveguides in combination with some dielectrics has been determined.

Design and optimization of gold/silver slotted filled with Air/SiO_2 MDM waveguide was achieved. Obtained results demonstrated the optical sensing capability of the afore said designed device with the respect to the change in the refractive index of a known liquid (analyte). A design methodology was developed to evaluate the influence of Air and SiO_2 on slot waveguide in light of various parameters such as shape, size and symmetry and non-symmetry of metal films when placed at the end of the both faces of waveguide. Details of finding suitable design of a suitable multilayer sensor and slotted MDM waveguide with respect to its performance with the help of commercial software Finite Difference Time Domain has been presented to understand the mutual agreement with the experimental observation.

A comparison of sensitivity and detection accuracy using multilayer (metal layer combination of gold, silver and dielectric layer of SiO_2 and TiO_2) and gratings was achieved in order to maintain high performance. In the year 2008, T. Allosp et al. [117] utilized the multilayer concept with base coatings of (germanium), dielectric (silicon dioxide) in conjunction with metals to develop SPR sensor with enhanced senstivity capable of detecting different chemical concentrations. Further, in 2011 Hu and Liu [88] opened the possibility of grating coupled bimetallic layered SPR sensor with angular interrogation method for enhancing detection accuracy upto 0.93^0. All the work discussed here contribute to design a simple and economical biosensing system in interest of public health.

Finally a suitable and high performance based SPR sensor in using multilayer and gratings was designed for detecting biomarkers Carcinoembryonic Antigen (CEA) & Epidermal

Growth Receptor (EGFR) of Lung cancer using Vroman effect. The concentration of both biomarkers have 2-5 $\mu g/ml$ and in human serum. Change in concentration of both the biomarkers caused a shift in wavelength of reflectance dip and may paved a way for early detection of lung cancer which further make out an delightful start for public health. Other than biological analysis, this multilayered and grating based SPR waveguide sensors offers numerous advantages in chemical and food processing.

2.9 Outline of Thesis

The thesis will be organized into five chapters. A brief outline is given below:

- **Chapter 1**: This chapter introduces the basic introduction along with motivation of research. It also covers theoretical concepts. We also describe the detailed description of optical sensors, their principle of operation, in comparison with surface plasmon resonance (SPR) waveguide sensor.
- **Chapter 2**: Survey of literature and prominent research gaps are present in this chapter. Furthermore, research objectives with their respective methodology, used in this study are defined in the chapter.
- **Chapter 3**: This chapter study the effect of various key parameters for designing the SPR waveguide biosensor.This chapter also explains the effect of gratings along with multilayer structure for various applications.
- **Chapter 4**: This chapter describe the proposed design with different plasmonic metals along with different dielectric to enhance the senstivity and detection accuracy for the detection of biological species and different chemical components.
- **Chapter 5**: The chapter enlists the major findings and contributions of the thesis. It also presents possible future research directions. The present work shows a good impact of SPR based sensor on commercial sensors by introducing the multilayer and grating effect. It was also found that multilayer not only overcome the shortcomings but with optimized design meet the senstivity and accuracy criteria. It was also observed that presence of different dielectric combination with metals produce better wavelength shift that is very useful for medical diagnosis.

Chapter 3

Performance Analysis of SPR Waveguide

In this chapter, analysis of parameters that affect the characteristics of SPR waveguide sensors have been described. In Chapter 1, theory of surface plasmons on metal/dielectric waveguides and their properties are discussed. Several techniques have been studied for coupling waveguide modes to guided modes which satisfy the resonance condition in terms of propagation constant. A set of differential equations is employed to obtain the solutions for modal amplitudes along the waveguide for periodic perturbations. In addition to this transfer matrix method is also extensively used for obtaining clear solutions for more complex structures. In this chapter, results of MDM waveguide has been presented to review the properties of SPR sensor. A brief introduction about the parameters is included in chapter 1; the following section detail about the parameters that affect the performance of SPR sensor.

3.1 Main Performance Characteristics

Generally a SPR sensor is operated on the phenomena where characteristics of light wave are modulated according to the refractive index in the form of coupling angle, coupling wavelength, intensity, phase and polarization. The important characteristics that describe the performance of SPR waveguide sensor are linearity, senstivity, accuracy, limit of detection, dynamic range and reproducibility [132, 133].

1. Linearity

   Sensor linearity is totally concerned with the concentration of analyte and refractive index. It can be defined as a relationship between the concentration of analyte and sensor output. The relationship was observed to be linear over a prescribed range of refractive index. Linearity prevent from calibration of sensor. But generally biosensor do not have linear response therefore they can be calibrated carefully.

2. Accuracy

   Accuracy is described as a close agreement between the true vale and measured value of concentration of analyte or refractive index. It is usually written as a percentage ratio of error and output of sensor.

3. Dynamic range

Dynamic range of SPR sensor can be described as values of refractive index on which sensor can measure with a specified accuracy. In SPR biosensors, it can be better defined by range of concentration of analyte over which a sensor can detect the lower concentration with the specified accuracy.

4. Limit of detection

LOD defined as ability of sensor to detect the analyte. It was further defined by International Union of Pure and Applied Chemistry and written as [134]

$$c_{LOD} = \frac{1}{S_c} m\sigma_{blank}$$

where S_c denotes the sensor senstivity and m denotes the numerical factor chosen as per desired confidence level while σ_{blank} is the standard deviation of the blank measurements.

5. Sensitivity

The sensitivity of sensor can be defined as ratio of change in light characteristics (i.e. angle, wavelength) to the change in the refractive index. The sensitivity was more detailed with wavelength modulation or interrogation method. In SPR biosensors, sensitivity will be read by breaking into two parts $S_c = S_{RIw}S_{RI2}$; where S_{RIw} related to the excitation method of surface plasmons and modulation approach and is also referred to instrumental contribution. S_{RI2} totally depends upon the bulk refractive index change. Where $S_{RIw} = \frac{\delta\lambda_r}{\delta n_{eff}} \frac{\delta n_{eff}}{\delta n}$ For a waveguide SPR sensor, the sensitivity can be rewritten in terms of dispersion as [134]

$$(\frac{\delta\lambda_r}{\delta n_{eff}}) = \frac{1}{\frac{dn_w}{d\lambda} - \frac{dn_{eff}}{d\lambda}}$$

where the $dn_{eff}/d\lambda$, $dn_w/d\lambda$ are the dispersion of effective index of surface plasmon and dispersion of the waveguide respectively.

3.2 Introduction of MDM waveguides

Recently, a renewed interest has been observed in metallic structures to explore optical properties. This has ultimately minimised the dimensions or structures of optical devices. Patterning of metals has added to the reduction in the size of the structures [135, 136]. Electromagnetic oscillations generated due to free charge density fluctuations that propagate at the interface of metal and dielectric are known as Surface Plasmons [137]. Surface plasmons have gained more interest of researchers as it can propagate through subwavelength apertures [138, 139]. Multilayered metallic nanostructure is also attaining focus compared to single layered metallic interface as multilayered structure has an advantage of improved optical responses, as it is using same metals at both the ends which having plasmonic behaviour to obtain MDM structures [66].

Metal-Dielectric-Metal (MDM) structure has a characteristic capacity of squeezing the surface plasmon modes in the dielectric region. Improved computational methods have resulted into better understanding of plasmonic behaviour of metallic-dielectric-metallic structures. On the other hand better fabrication methods shows a promising behaviour to use complex metal structures for various sensing applications [140]. Surface plasmons are usually associated with high propagation losses due to imaginary part of dielectric constant of metal.

A novel silicon waveguide fabricated by Qianfan Xu et al. [141] is capable of confining light in nano structures with a material of low refractive index. Research group of Prade [54] proposed a waveguide for nanometric focusing of light with different metal layers along with a dielectric core. Ning-Ning Feng et al. [58] investigated a slot waveguide with dielectric having high refractive index with deep-subwavelength-sized metal structures. Afore said waveguide also achieved high transmission without compromising the overall propagation loss.

Allosp et al. [97] investigated the multilayer coating with a combination of Ge /SiO_2 /Pt /Ag /Au for different refractive indices in aqueous regime. The above cited findings highlight the propagation and focusing of light using MDM structures for different applications with different refractive index materials. None of the above discussed about the multilayer MDM structures with high refractive index materials. They can be further used for high performance sensing applications.

In line with this, surface plasmons in slot metallic-dielectric-metallic structures have been studied and proposed with different slot material e.g. Air/ Silicondioxide having different thickness. A detailed study is carried out for understanding the trade-off between sensitivity & propagation length as well as prorogation loss with extra ordinary transmission. The problem of mitigation along the single layer metal dielectric structures has been discussed. Numerical method along with simulation method (FDTD) is employed for better understanding the reflectivity spectra.

3.3 Theory

Surface Plasmons are oscillations that excited at the metal dielectric interface when the momentum of the incident light matches their momentum. For a good sensing region, light characteristics i.e. wavelength, angle and phase is highly sensitive to variation of sensing material refractive index. [47]. Quantum Physics illustrate that the modification of energy levels are similar to the modification of dispersion relation, which are frequently occurred. e.g. if two quantum wells with same energy levels are brought near to each other, a coupling exists between the associated wave functions which further results that difference in energy will increase [142].

Accordingly mutual closeness between two wave functions in terms of space and energy increases, that causes repulsion. Surface plasmons employs the same theory as they are also waves of surface charges and energy splitting may also exhibit. Therefore, a dielectric layer surrounded by same metal layer from both sides form a symmetrical metal-dielectric-metal (MDM) structure. Further, surface plasmon dispersion relation is modified using the MDM structure and the presence of metal layer at both the ends ensures coupling at the interfaces. It also increases the coupling strength by reducing the separation between them [63]. Using Maxwell's theory, surface plasmon dispersion relation is rewritten taking into consideration of MDM structures [143],

$$[\frac{\alpha_m}{\epsilon_m} + \frac{\alpha_d}{\epsilon_d}\coth(\alpha_d a)][\frac{\alpha_m}{\epsilon_m} + \frac{\alpha_d}{\epsilon_d}\tanh(\alpha_d a)] = 0$$

Where d and m refers to dielectric and metal respectively, & the wave equation should be satisfied with the evanescent parameters α_m and α_d and in-plane wave vector k_x [143]

$$k^2{}_x - \alpha^2{}_{m,d} = \epsilon_{m,d}\frac{\omega^2}{c^2}$$

Similarly, for an asymmetrical MDM waveguide having three layer slotted structure can be expressed using the characteristic equations for SPP Mode. [143]

$$(\frac{\epsilon^2{}_{r1}}{k^2{}_1} + \frac{\epsilon_{r2}\epsilon_{r3}}{k_2 k_3})\tanh(k_1 d) + \frac{\epsilon_{r1}}{k_1}(\frac{\epsilon_{r2}}{k_2} + \frac{\epsilon_{r3}}{k_3}) = 0$$

3.4 MDM Waveguide Design

Fig 4.1 illustrates the design of proposed slotted MDM structure. It consists of a sandwich structure of symmetric metal layers and dielectric layer (Silicon) with a slot in it. 100 nm thick silicon layer is there with gold layer on both side with thickness $h_{Au} = 100$ nm. In continuation with that $h_{Air} = 10$ nm (air gap is between 10-50 nm wide) either single mode operation or TM Mode, the air gap should not be greater than 50 nm at 900 nm wavelength. For a width of air gap below 10 nm, waveguide cannot function in

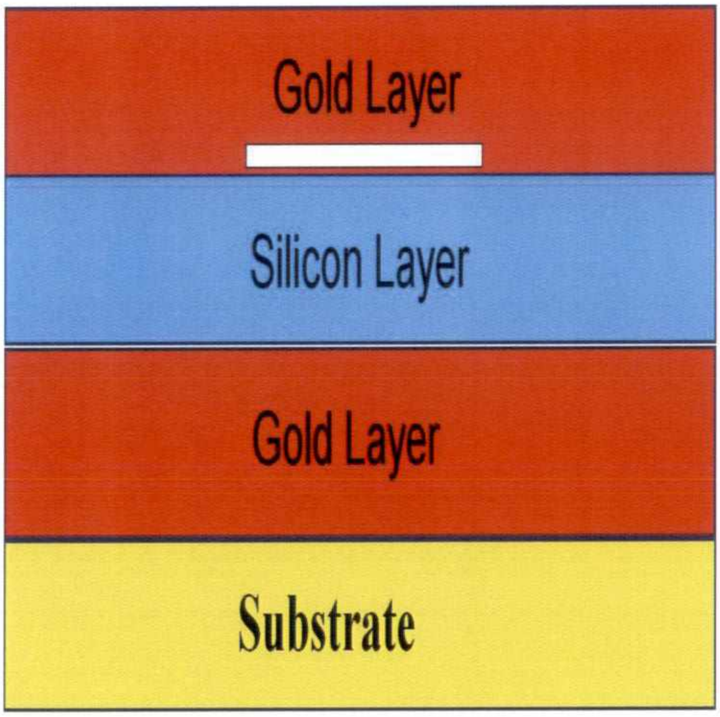

Figure 3.1: Schematic of Slotted MDM waveguide in which top gold having thickness of 100 nm carries a air gap adjacent to silicon layer

TM mode, therefore Surface Plasmons waves does not exist. Presence of air gap into the top gold layer enhances the sensing capability as the same waveguide is with SiO_2 and without air gap does not. Certain geometrical parameters play an important role in sensing performance of the proposed design. We examined the guiding performance by observing the h_{Air}, h_{SiO_2}.

3.5 Results and Discussion

The waveguide geometry affect the distribution of electric field as well as magnetic field (H_y). The simulation of the proposed waveguide for certain characteristics is done through Finite Difference Time Domain. The Electric field of light passes perpendicularly through the guiding region, the standing-wave equation can describe the resonant peaks of the surface plasmon dispersion. The effective index (n_{eff}) of waveguide is altered due to the thickness of consecutive layers. Therefore height of slotted gap (e.g. Air or Silicon dioxide) which varies accordingly slightly change the effective index (n_{eff}). By keeping width of

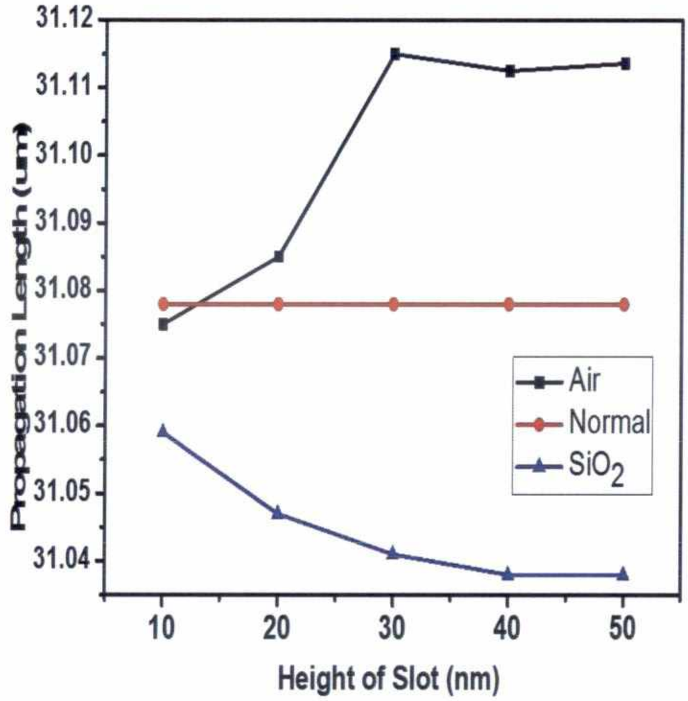

Figure 3.2: Effect of height of slot on the propagation length

silicondioxide and Air near to 50 nm, air slotted waveguide have $n_{eff} = 1.527$ as real part, while it extends to 1.54 in case of Silicon dioxide. It is also noticed that for low losses, the value of (n_{eff}) should be lesser. $L_{pop}\ (\mu m) = \frac{\lambda}{4n_{eff(imag)}}$ is used for calculating the propagation length for aforesaid MDM waveguide. Obtained propagation length with air slot waveguide is more than the silicon dioxide and without slot waveguide. Fig 3.2 shows the effect of variation of slot height on the propagation length. Moreover, the transmission of slotted MDM structure is analysed for obtaining high sensitivity with respect to change in refractive index for any sensing medium. Accordingly, a tremendous achievement in the transmittance is achieved with a certain value of air gap while it is lower in case

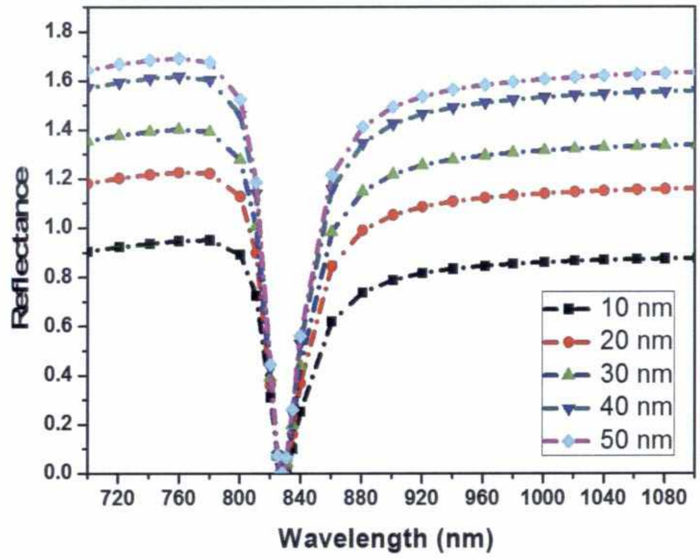

Figure 3.3: Effect of Air gap on the transmittance

of SiO_2 as compared to air. This is shown in fig 3.3 & 3.4. Further, the variation

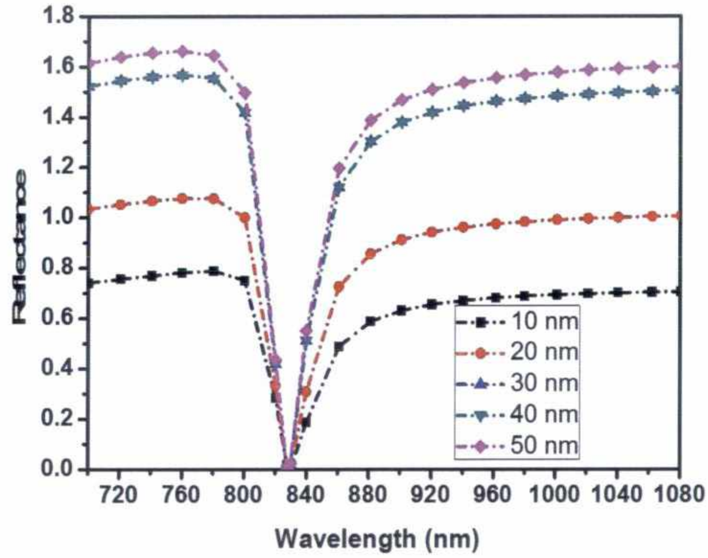

Figure 3.4: Effect of Silicon dioxide (SiO_2) on the transmittance

of refractive index for Air/SiO_2 slotted waveguide in terms of sensitivity is observed as shown in fig 3.5 by keeping air gap height = 50 nm. Several geometrical parameters e.g. resonance wavelength, refractive index of the sensing layer alters the senstivity. If the variation in refractive index of sensing layer is denoted by Δn_s, then resonance wavelength experiences a shift of $\Delta\lambda_s$. A shift of 18 nm in resonance wavelength with a change of 0.01 in refractive index in sensing layer is obtained with designed waveguide. In contrast

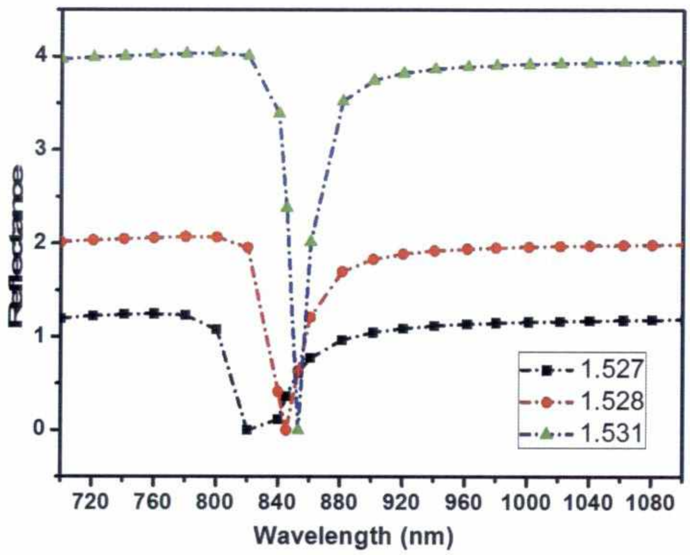

Figure 3.5: Effect of refractive index change on the transmittance in slotted Air

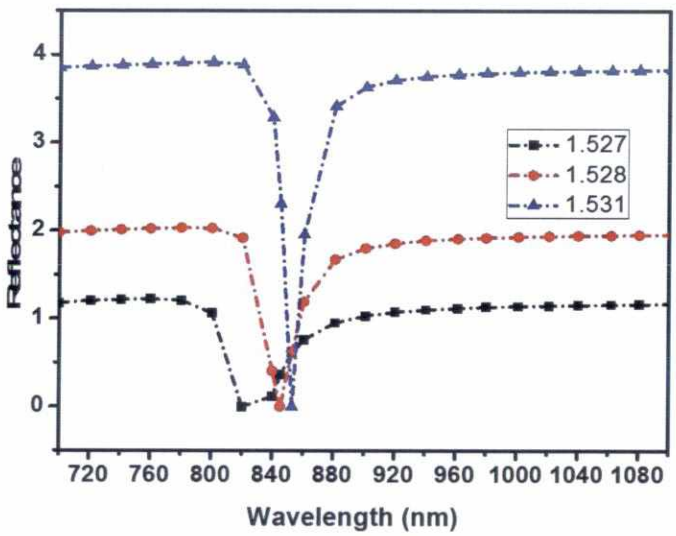

Figure 3.6: Effect of refractive index change on the transmittance in slotted Silicondioxide

to this, MDM waveguide with silicon dioxide of h_{Si} = 10 nm is shown a shift of 16 nm for same change in refractive index of sensing layer as shown in fig 3.5 and fig 3.6. The obtained refractive index variation shows effective augmentation of 1600 RIU^{-1} and 1800 RIU^{-1} as shown in fig 3.5 & fig 3.6 w.r.t the obtained by [97].

3.6 Summary

In this chapter, various parameters in terms of performance of SPR waveguide has been discussed. This chapter also outlined the theoretical modeling for MDM waveguide in lossy media. Slotted Metal-dielectric-Metal waveguide with different material (i.e. SiO_2 and Air) have been investigated in terms of propagation length, senstivity etc. Typical transmission curves in sight of extra ordinary transmission for MDM are shown using FDTD.

Chapter 4

High Performance Sensor

Based on the previous chapter outlines, extra ordinary transmission, sensitivity and propagation length for MDM SPR waveguide are investigated and discussed in detail. In view of the findings, this chapter outlines a new layout of multilayer in combination with gratings for attaining a high performance sensor. Several noble metals have been studied and their effect on the proposed waveguide in terms of sensitivity and detection accuracy is also explored in detail. This chapter also outline the effects of gratings and different modes for multilayer SPR waveguide. This chapter also focuses on the the second objective that is to determine the performance of SPR waveguide sensor using different metals. A combination of two metals in consecutive layers is presented with a simple design to obtain better sensitivity and high detection accuracy.

4.1 Introduction

In the recent years, optical properties of metallic structures have shown a renewed interest. This has ultimately minimised the structures or dimensions of optical devices. Patterning of metals has added to the reduction in the size of the structures [135, 144]. Meanwhile, surface plasmon resonance (SPR) based optical sensors have marked their presence due to the emerging biosensing application areas. SPR biosensors have been widely explored and several geometries related to SPR configuration have been developed [48, 145].

To detect small changes in refractive index, for example that near to metal-dielectric, SPR technology was first introduced. In addition to that, it has several advantages like high sensitivity, fast speed response etc. Previously SPR biosensing technology used the Kretschmann configuration which constituted the prism based implementation of attenuated total reflection [146]. Electromagnetic oscillations generated due to the free charge density fluctuations that propagate at the interface of metal and dielectric are known as Surface Plasmons [137]. Surface plasmons have gained more interest of researchers as it can propagate through subwavelength apertures [138]. Multilayered metallic nanostructure is also attaining focus compared to single layered metallic interface as multilayered structure has an advantage of improved optical responses, as it is using same metals at both the ends which having plasmonic behaviour to obtain MDM structures [66]. It is worth mentioning that performance of SPR sensor will be determined by dispersion properties of metals [147]. Generally, metals which show dispersion properties have SPR characteristics like silver (Ag), gold (Au) and aluminium (Al) etc.

Further each SPR metal exhibits its own SPR properties, such as aluminium exhibit narrower resonance curve while gold carries better chemical stability and absorption coefficient [48]. Although Al have some issues over chemical stability, so to overcome this issue we have simulated the multilayered grated waveguide of gold and aluminium. P. West et al. [148] created a new window for alternate plasmonics materials with the aspects of fabrication. They also presented the comparative study of different type of metals, metal alloys and doped semiconductors. In line with this S. Xiao et al. [85] also stated the theory of enhanced transmission through a gold film with sub wavelength array holes.

M. Jory et al. [6] demonstrated a prototype of SPR sensor with gratings, with angular interrogation method. In continuation to this, C.Hu et al. [88] also proposed a high performance grating coupled SPR sensor to achieve angular sensitivity of 187.2^0/RIU. T. Srivastava et al. [48] proposed a perioidic multilayered SPR waveguide sensor with SPR active metals. Some of them only focused on the angular interrogation which was very complex in optimizing and calibration. Moreover, angular interrogation method was not so accurate vide T. Srivastava et al. [48]. While maintaining a periodic multilayered waveguide is impractical for obtaining high end accuracy and sensitivity. In view of above, we have investigated a high performance multilayered grating SPR sensor and optimized it with few SPR metals i.e. gold (Au) & aluminium (Al).

4.2 Theory

The proposed MSPGW (Multilayered surface plasmon grated waveguide) geometry based on surface plasmons is shown in fig 4.1. It includes a stacked layer of metal and dielectric with periodic gratings. Assuming that the waveguide is fabricated with core of silica having a refractive index of 1.5, with a periodic grating of $\Lambda = 100$ nm filled with silver. The core is sandwiched in between multilayer of metals i.e. gold and aluminium of thickness 10 & 5 nm. Metal layer is further followed by an analyte i.e. sodium chloride of refractive index 1.360. In this geometry, the interface between metal and dielectric is modulated with a period Λ. According to the grating equation $\sin\theta = \frac{n\lambda}{\Lambda}$, where ($\Lambda$ is the grating pitch, λ is the wavelength of light, θ is the angle of diffraction & n is the

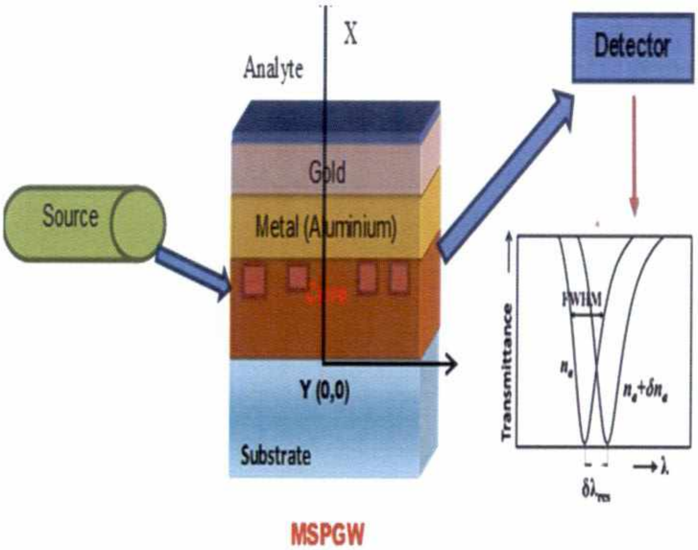

Figure 4.1: Proposed configuration of MSPGW geometry

diffraction order) [6, 9]. So general equation by employing the surface plasmons [6].

$$k_n = k_0 \sin\theta \pm \frac{2\pi n}{\Lambda} \tag{4.1}$$

where k_o is the wavevector of incident photon and k_n is the grating plane surface wavevector. Normally surface plasmons are excited at the metal interface when their momentum matches with the momentum of the wavevector or incident photon of SPR along the said interface is equal to k_n, by keeping θ fixed and varying the wavelength. The coupling condition between the guided modes and surface plasmons would be matched when both the propagation constants of two waves became equal.

$$\beta_{mode} = Re\{\beta_{SP}\} \tag{4.2}$$

where β_{mode} denotes the propagation constant of waveguide mode. Normally, resonance wavelength is highly sensitive to the refractive index change of sensing material for a sensing medium [47]. Further, light from a tunable laser source is passed through the proposed waveguide core using optical devices and suitable detector. As discussed above, transmission spectrum shows minimum value at a particular resonance wavelength. Similarly, a slight change in refractive index of analyte brings good shift in wavelength spectrum that forms the essentials for refractive index sensing.

In this manner, sensor is basically qualified in terms of sensitivity (S_n) and accuracy detection (DA). Due to variation in refractive index of analyte, the variation in resonance wavelength is obtained. Hence sensitivity is defined as ratio of variation in resonance wavelength to variation in refractive index of analyte. Further detection accuracy DA = $\frac{1}{FWHM}$ (Full width at half minimum) of transmission curve.

4.3 Results and Discussions

To design the proposed sensor, first we determines the suitable thickness of metal layers. Surface plasmons exhibit TM wave in-turn also called p-polarized light. To better understand the phenomena of p-polarized light at transmission output, we follows a general equation of transmitted power normalized with source power and written as [77]

$$P(f) = exp^{(}-\frac{4\pi}{\lambda}\iota n_{eff}L)$$

Where n_{eff} is the effective refractive index of surface plasmons. Here we take the

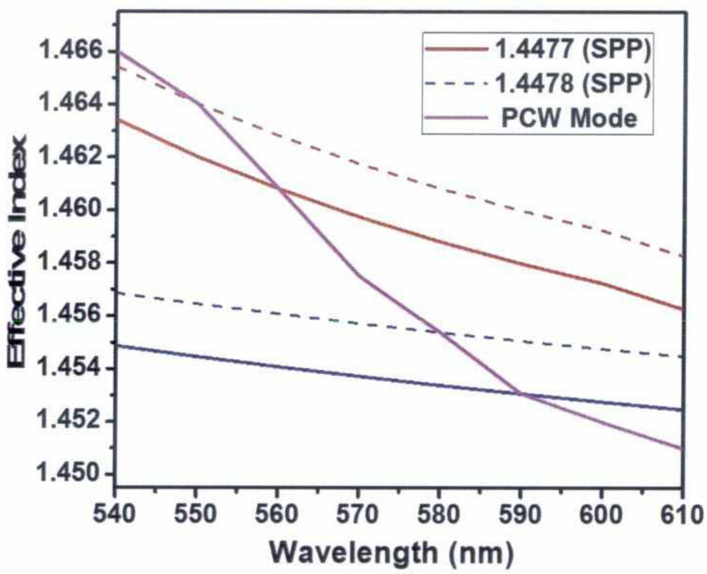

Figure 4.2: Variation with effective refractive index w.r.t wavelength for exciting mode of Multilayer grating waveguide and SPP of plasmonic waveguide for gold and aluminium at n_a = 1.4470 & 1.4471

imaginary part of effective refractive index to show the dip of resonance wavelength. A series of simulations is also carried out to investigate the performance of proposed sensor through FDTD method. Standard method i.e. mode solver is used to calculate the result and also find out the mode effective indices of multilayer periodic gratings. It is assumed that refractive index of substrate n_s = 1 and the thickness of metal layer = 10 nm. In order to find out the impact of metal layer with periodic gratings with following variations

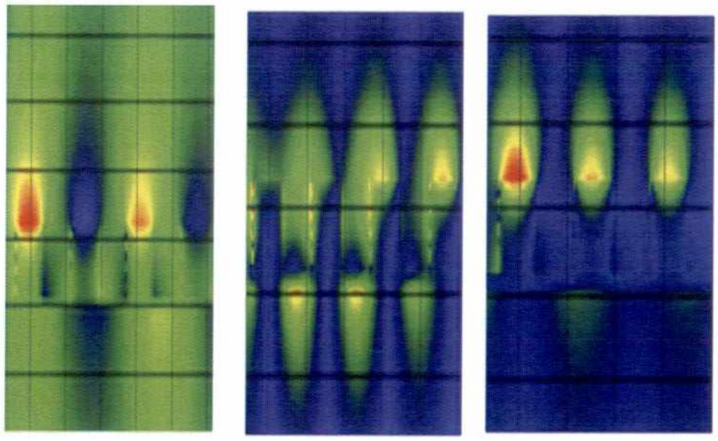

Figure 4.3: Field penetration H_y for all combination of SPR active metals at $n_a = 1.330$

i.e. (i) gratings with gold analyte (ii) Aluminium based MSPGW sensor as per design parameters mentioned above. The changes in mode effective index (n_{eff}) with respect to the wavelength are shown in fig 4.2. The value of dielectric constants of gold, silver and aluminium is taken from E.D. Palik [149]. The effective refractive index variation with existing modes using band solver is shown in fig 4.3. Transmittance of MSPGW shown in fig 4.4 as a function of wavelength is calculated by taking into account that coupling length is almost equal to the interaction length. The power which is launched in the core of waveguide is assumed to be unity. According to fig 4.4, it is clearly understood that aluminium based sensor ($\Delta\lambda$ = 1.4 nm) have narrower transmission curve than gold ($\Delta\lambda$ = 3.2 nm).

Generally, the smaller value of $\Delta\lambda$ resembles the weak dispersion of surface plasmon mode at the analyte and metal interface. To overcome the poor stability of aluminium, we proposes a multilayer gratings combination of metals (5 nm Al with 10 nm gold with which gratings of silver having a periodicity of 100 nm) and finds a combined resonance shift ($\Delta\lambda$ = 2.5 nm). Therefore, gratings filled with silver have their impact on *sensor's* characteristics. Gold layer above the dielectric layer not only protect them from oxidation, but also improves the performance of sensor.

It is worth mentioning here that silver has higher sensitivity with respect to gold and aluminium. Although, transmittance also drops for the above said proposed geometry, may be due to unequal losses at metal analyte interface but it will not alter the sensitivity i.e. S_n and detection accuracy (DA). In order to add some physical understanding, the

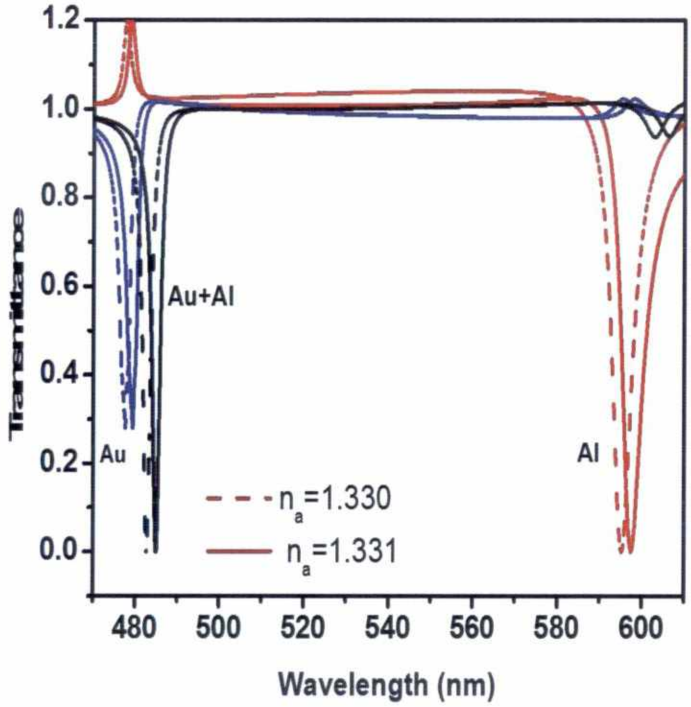

Figure 4.4: Transmittance through MSPGW core for different metals (Au, Al, Au+Al) at $n_a = 1.330$ and $n_a = 1.331$ ($n_s = 1.00$)

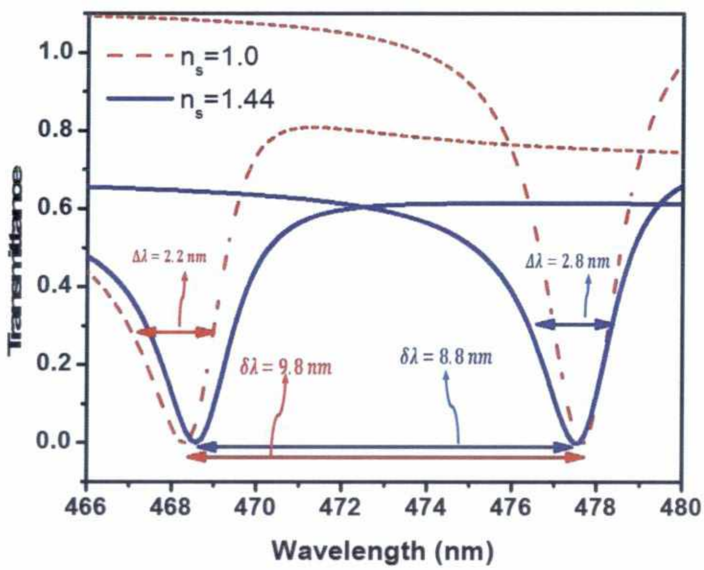

Figure 4.5: Transmittance through core for different substrate as a function of wavelength ($n_s = 1.00$ & $n_s = 1.44$) for analyte refractive index 1.360 and 1.361 for Al+Au grating based waveguide

modal field of MSPGW for particular or fundamental mode for the proposed configuration i.e. Au + Al is shown in fig 4.6 and 4.7. Sensors become more attractive due to its large penetration depth in analyte. So, said sensor with Al $\sim$ 26.0 μm having more penetration depth than the gold $\sim$ 11.2 μm. For measuring the performance of sensor, the DA and S_n of the proposed sensor for above said SPR active metals i.e. Al, Au & Au+Al is calculated as shown in fig 4.6. This figure illustrates that S_n increases sharply, due to slight increase in the mode effective index n_{SPP} with variation of refractive index of analyte. From the fig 4.7, it is understood that sensor based on gold shows highest S_n (9400 nm RIU^{-1} at $n_a = 1.360$), but smallest detection accuracy ($\sim$ 120 μm^{-1}) which further includes the less accurate detection of analyte index change. However, sensor based on aluminium have lowest value of S_n $\sim$ 8800 nm RIU^{-1} but highest DA $\sim$ 354 μm^{-1} that further determine higher accuracy. But here we merge both the layer with grating configuration that shows a promise change in detection accuracy and have a smallest value of sensitivity. The above results show the trade-off between the detection accuracy and sensitivity with respect of analyte change that have to be augmented for better performance. From fig 4.5, we relate the transmittance through the core of silica and air substrate by FDTD method for Al+Au MSPGW SPP modes. By the calculated values of S_n = 6400 nm RIU^{-1} and DA $\sim$ 310 μm^{-1} at refractive index at $n_a = 1.360$ ($n_s = 1.0$). A slight increment in the S_n $\sim$ 7600 nm RIU^{-1} w.r.t [48] is observed while DA = 230 μm^{-1} reduces slightly which proves that high refractive index value gains a sharp change in the performance of sensor as compared to [88]. In case of high index, the dispersion of multilayer waveguide is marginally high as compared to low index material that further effect the S_n and DA. We also analyse that electric field penetration is small in substrate which includes the weaker interaction of different modal field with substrate.

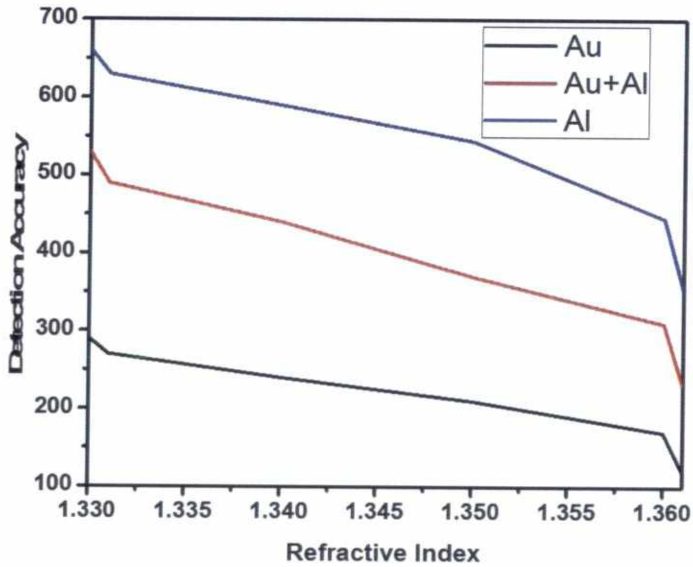

Figure 4.6: Variation of detection accuracy w.r.t refractive index change

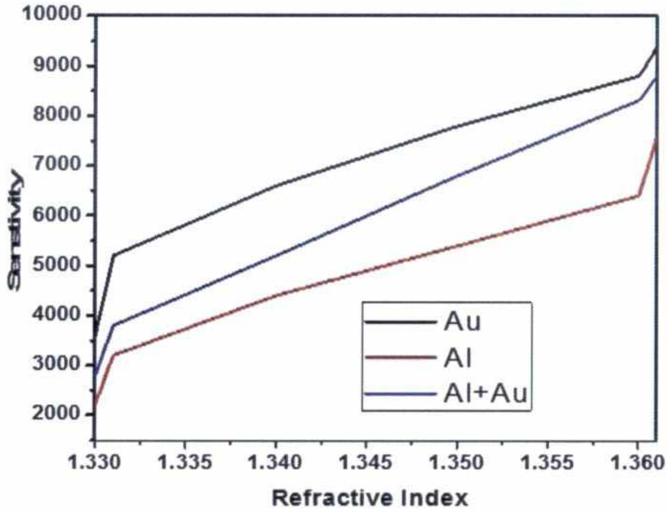

Figure 4.7: Variation of senstivity w.r.t refractive index change

Overall, it has low impact on sensor performance as index of substrate changes.

4.4 Summary

A high performance multilayer grated SPR sensor has been designed and discussed in detail. The presented description involves the gold and aluminium coated SPR waveguide sensor for a promising performance. The grating based SPR sensor offers a good senstivity response and repeatability. The effect of thickness of multilayer along with gratings on the performance of SPR waveguide sensor has been studied. It is observed that sensor with small gratings and lighter thickness of metal layer having have higher senstivity in respect of refractive index change. The combination of gold with aluminium played a vital role for smooth detection and better accuracy.

Chapter 5

SPR based Biosensor for Detection of Lung Cancer

Based on the study presented in previous chapter, Chapter 5 includes the design and development of SPR waveguide sensor based on multilayer and grating for detection of lung cancer. A three layer concept consists of two metal layer alongwith dielectric layer of TiO_2. Said design has been investigated for different metal thickness as well as for different grating periods. Optimization for said geometry is being carried out with investigated grating period and bi-metallic layer thickness for achieving the better senstivity and detection accuracy. The multilayered grating structure is employed for early detection of lung cancer with two biomarkers i.e. (CEA and EGFR). The chapter is organized in three important sections i.e. Introduction which involves brief review along with general description about lung cancer biomarkers. Basic description about sensor design discussed in succeeding section while performance and optimization of SPR waveguide sensor has also been discussed along with Vroman effect.

5.1 Introduction

Diseases can be classified as infectious and non-infectious diseases. Non-infectious diseases can be chronic disease and have higher incidence worldwide resulting in rapid death. Asthma, heart disease, kidney disease, cancer etc. are chronic diseases. Cancer can be classified depending on the location of the tissue affected. Lung cancer is one of the type of cancer which is said to be the result of smoking. Lung cancer is mostly diagnosed in the later stages as it is confused with Tuberculosis and COPD diseases of chest. Treatment of lung cancer is a long process and survival rate in India is very less (i.e. almost 5 year)[150]. Present diagnosis methods (biopsy, sputum cytology) which are available are either invasive or too much expensive. Increasing incidence of cancer has enforced us for the development of highly sensitive, precise and real time device for the diagnosis [124] of the disease so that better prognosis can be done. Recently, researchers and scientists have developed fast and inexpensive techniques for the detection of cancer biomarker protein [151] using biosensors, as cancer can be cured if early detected. Biosensor is a device which has the competence to analyse different samples i.e. blood or clinical samples. Recent advances in biosensor technology is leading to miniaturization of sensing devices. Several biomarkers have been identified for detecting the cancer effectively that further categorized to type of cancer. Among blood-based biomarkers, serum CEA is most extensively examined, and several studies showed that serum CEA was a useful marker not only to discriminate lung cancer, especially adenocarcinoma of the lung, from benign diseases but also to determine tumor progression and prognosis [152].

CEA is a glycoprotein which has a significant role in cell adhesion. It starts its production during fetal development, however it stops producing before birth. Therefore,blood of a healthy adult does not have CEA. Whereas, CEA is widely expressed in cancer cells. Its observed that majority of cancers such as colorectal, gastric, pancreatic cancers express CEA in the majority of non-small cell lung cancers and other carcinoma types, such as squamous cell cancer [153]. Despite promising results, routine use of serum CEA is not recommended mainly due to its insufficient sensitivity and/or specificity as well as lack of reproducibility of the results.

5070% of human primary breast, lung and colon carcinoma, are observed to over-express Epidermal growth factor receptor (EGFR) whereas it is not usually expressed in hematopoietic cells. It is a transmembrane glycoprotein/ cell surface receptor with an extracellular ligand binding domain, a transmembrane lipophilic segment and an intracellular tyrosine kinase , its of 170kDa.[154]. Epidermal growth factor receptor is a member of the ErbB tyrosine kinase receptor family which includes four proteins encoded by the cERBB proto-oncogene, namely ErbB1 (EGFR), ErbB2 (HER2/neu), ErbB3 (HER3)and ErbB4 (HER4). Binding of ligand leads to dimerization of the receptor and intrinsic protein tyrosine kinase activity activation leading to the transduction of signaling pathways involved in proliferation, cell division and differentiation [155].

Intracellular EGFR signaling is mediated by MAP kinase and AKT signalling pathway. MAP kinase induction biologically leads to increased expression of proteins governing cell-cycle regulation. AKT is an anti-apoptotic kinase which has its role in cell survival angiogenesis. It is also linked to activation of matrix metalloproteinase protein facilitating tumor growth and development[156] In this manner, Carcinoembryonic antigen (CEA) and Epidermal growth factor receptor (EGFR) have extensively studied as lung cancer biomarkers in terms of diagnosis [117]. CEA and EGFR biomarker is a type of protein and have a certain limit value 3-5 ng/ml and 2-20 ug/ml in our body [157]. According to the prescribed value, both biomarker have a accepted effective refractive index range 1.32-1.37 and 1.66-1.70 [158]. Blood cells contain the above said biomarkers however, cancerous blood cells have higher refractive index than the normal blood cells. Surface plasmon resonance based biosensor have emerged as indispensable tool in the field of biomedical research [158]. Optical SPR based biosensor works on the principle of change in the effective refractive index. Few techniques have been developed with different SPR geometries in field of biosensor area but all present techniques have certain limitations i.e. low stability, lack of antibody diversity etc. In parallel to this, existing biosensor based analysis is very time consuming [159].

Conventional SPR biosensors have a problem of alignment and lacking of experimental precision. These devices are also not so compact [160, 142]. Traditional SPR biosensors generally uses glass as core and a single layer of thin metal film for excitation of surface plasmons. The propagation of light in the SPR biosensor can be understood by Maxwell equations [36]. The multilayer structure as defined in our previous work [161] has the ability to cuddle in the adjacent dielectric region and consistent fabrication techniques have made it simple for complex metal layer structures [147, 162]. SPR metals have dispersion properties which further exhibit better chemical stability and absorption coefficient. SPR sensors have been demonstrated for detection of pesticide [114], blood sugar [5], breast cancer biomarkers [160] and much more applications. So, here we have reported the development of grating based SPR waveguide biosensor for the detection of lung cancer biomarkers using Vroman effect. By extending Vroman effect and optimizing the sensor geometry, the aforesaid biosensor achieved sharp resonance peak and paved a way to high selectivity detection of lung cancer using biomarkers.

We elected wavelength interrogation method for a small change in refractive index which gives high detection accuracy and also enables good figure of merit. As per above illustration of Vroman effect, low wt component cells may be replaced by high wt component cells subsequently, the resonance wavelength shift to different resonance wavelengths. Fast FDTD algorithm with perfectly matched layer (PML) is used for analysis with boundary condition of absorption and reflectance [161].

5.2 Theory

In order to specify the cancer biomarker for biosensor, recognition material (antibodies) played an important role. The antibodies are fabricated as affinity material that can be further used as analyte for detection purpose. Further, these antibodies are applied to target the lung cancer biomarkers. We practiced the Vroman effect for optimum sensitive and highly selective detection, as selectivity was always a persistent problem in biomarker detection. Vroman effect utilize the molecular weight differences for the selectivity Blood cells having high molecular weight replaces the light molecular weight cells while vice-versa does not occur. The proposed bio-sensing platform is shown in fig 5.1. The proposed biosensor is a multilayered structure arranged in a schematic manner in air background having refractive index of 1.0 on wafer.

Presence of air in the background protects the biosensing platform from the problem of material dispersion and absorption. The compromised structure consists of 60 nm of dielectric layer of TiO_2, which is further followed by sandwich of two metal layers i.e. gold (10 nm) and aluminium (6 nm). The presence of aluminium provide narrower resonance curve while gold carries better chemical stability [161]. The dimensions of bio-sensor slab is in nm^2. In the proposed geometry, the metal and dielectric is separated with a period Λ. The detailed description has already been described in previous work [161] regarding input source, resonance wavelength for biosensing purpose. In this work, we

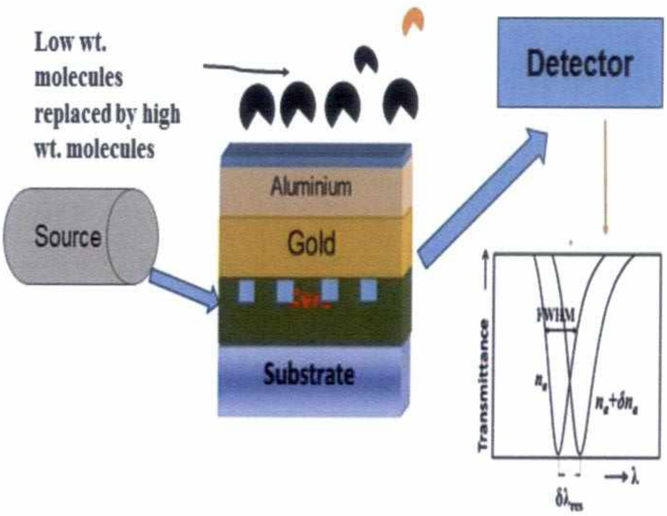

Figure 5.1: Multilayered grated SPR waveguide sensor structure with width of Aluminium layer = 6 nm, Gold layer = 10 nm and size of gratings = 140 nm

have presented a grating based multilayered structure for bio-sensing platform, and as discussed above it is easy to fabricate with slight alterations. By introducing grating period, a linear waveguide is formed as shown in fig 5.1. A periodic geometry further followed by a grating equation 5.2[6]

$$\sin\theta = \frac{n\lambda}{\Lambda}$$

where θ is the angle of diffraction, λ is the wavelength of light, Λ is the grating pitch and n is the diffraction order was used [6, 9]. We have induced Vroman effect which has improvised sensing. We also induced periods of different sizes to generalize the optimum sensing and detection accuracy. Further, the structure was optimized by altering the parameters, so as to obtain better sensing and detection accuracy. Optimization is achieved by changing two parameters i.e. the size of period and the height of metallic layers. Our main objective of optimization was to obtain a good shift in resonance wavelength adjacent to shift in refractive index for better sensitivity. Senstivity (S) is defined as ratio of obtained change in the resonance wavelength due to small change in refractive index. It is measured in terms of nm/RIU and it must be as high as possible [36]

$$S = \frac{\Delta\lambda}{\Delta n}$$

Where $\Delta\lambda$ is change in resonance wavelength and Δn is small change in refractive index. The detection accuracy is inversely proportional to obtained change in the wavelength at Full Width Half Maximum (FWHM). It is a unit less parameter and it should be as high as possible.

$$DA = \frac{1}{FWHM}$$

Where, FWHM is the difference of wavelengths obtained at 50 percent. To attain high DA, resonance peak should be narrow while greater shift is needed for higher sensitivity.

5.3 Vroman Effect

Selectivity has always been consistent problem in the present biosensor because bio-receptors having different affinity and specificity. Each bio-receptor have specific affinity that attracts various analyte for better selectivity [163]. Many bio-receptors i.e. antibodies, peptides etc. is being used to detect specific tumour cells. Apart from this, affinity of antibodies for binding the target analyte must be high but these have certain limitations i.e. low reproducibility and non-specific adsorption. Besides these limitations, integrating Self assembled monolayer (SAM) linking molecules by on the metal surface is another relevant problem. These methods are time consuming and intensive process. These limitations produced a bottle neck for high yield output of sensor. To overcome these limitations, a method of competitive protein exchange has been developed in 1960 by Vroman et al. [164]. In view of this, different molecules have different adsorption rate to a given surface.

While smaller molecules having lower weight can easily adsorb to surface so the phenom-

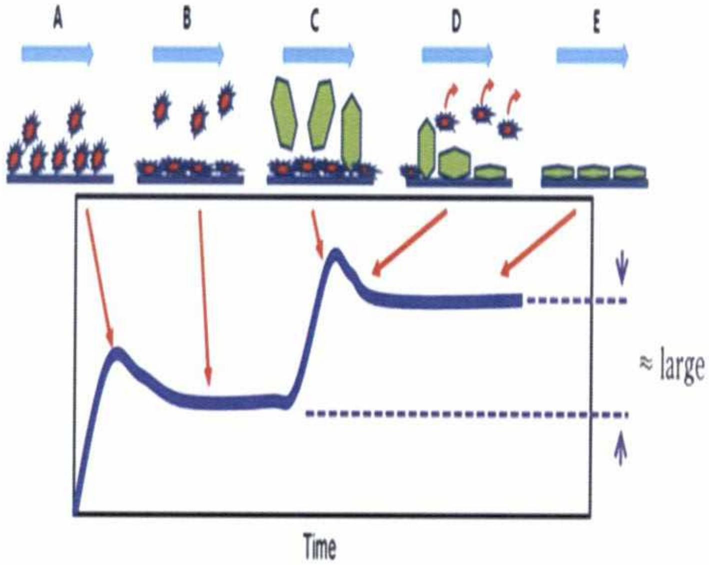

Figure 5.2: Variation of molecules density w.r.t to wavelength shift using Vroman effect

ena of proteins which is adsorbed on the surface may be replaced by arriving proteins subsequently having larger molecular weight [165] and protein exchange (means light weight molecules replaced by larger weight molecules but vice versa is not possible) is called Vroman effect. This method is totally depends upon the given sequence i.e. HK > fibrinogen > IgG > albumin [166] for blood as blood is involved in disease diagnosis and bio-compatible device & biological analysis [167].

5.4 Analysis for cancer bio-markers with Vroman effect

As per earlier discussion and shown in fig 5.1, the induced periodic gratings with the proposed multilayer geometry gave a resonance wavelength of $\sim 900nm$. To obtain efficient detection, we reduce the amount of blood sample to a minimum area on the analyte layer. According to the surface resonance effect propagation velocity get reduced when it is passed through different analytes as they have higher refractive indices compared to air and water, which further results in change in optical properties due to effective refractive change for smooth detection and measurement. Different blood samples having different lung cancer biomarkers have different permittivity (ϵ) whereas relation between refractive index and permittivity is given by $\epsilon = n^2$. The geometry is simulated with the blood samples of healthy people having refractive index of 1.32 and simulation done for different periodic gratings to observe the sensitivity and detection accuracy. On increasing the size

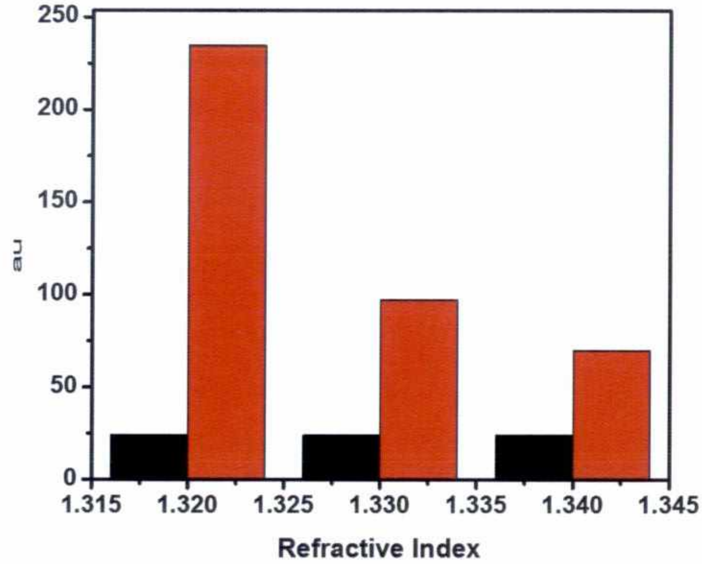

Figure 5.3: Variation of sensitivity and detection accuracy with the change in grating size of 140 nm

of gratings it is observed that though there are a small increment in the sensitivity, the detection accuracy decreases. On increasing the grating size beyond 140 nm, the change in resonance wavelength is observed along with steep decrement in the detection accuracy. Therefore, grating size of 140 nm as optimized structure in respect of simulation results is considered. While applying Vroman effect, the above discussed geometry favours the

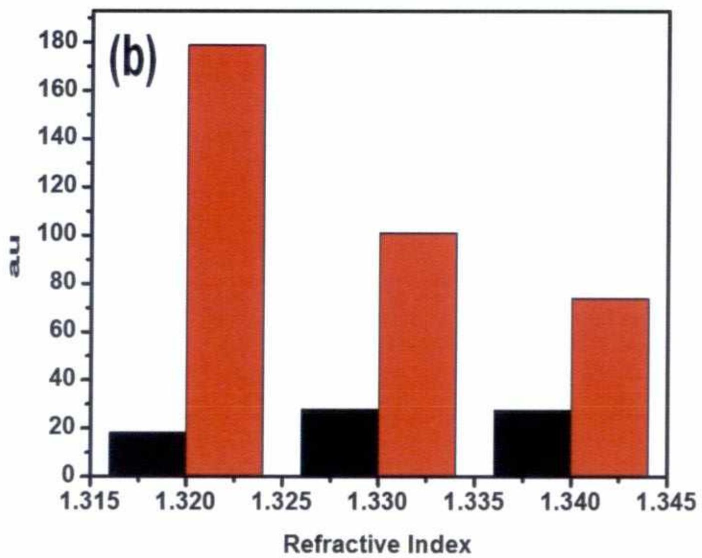

Figure 5.4: Variation of sensitivity and detection accuracy with the change in grating size of 130 nm

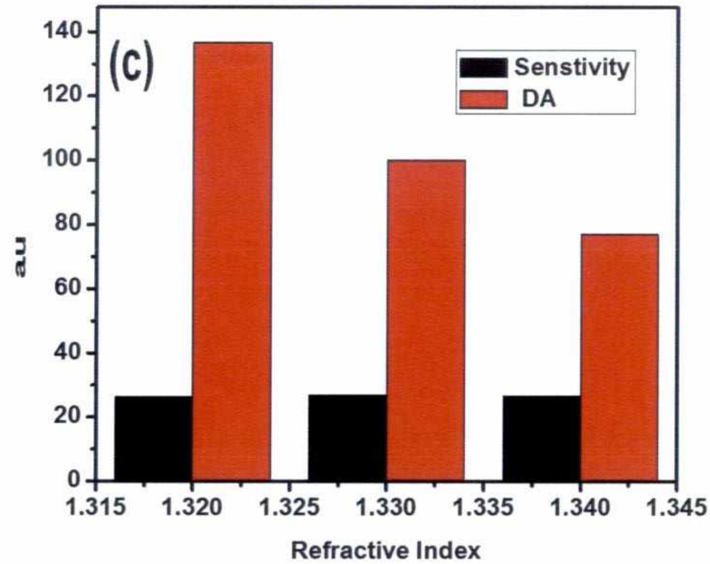

Figure 5.5: Variation of sensitivity and detection accuracy with the change in grating size of 120 nm

high outputs in respect of sensitivity with reasonable detection accuracy as shown in fig 5.3, 5.4 and 5.5.

The effect of variation of propagation of light [tunable light source (Zolix-LSH T50, China) ranging from 250 nm to 2700 nm] is observed on optical spectrum analyzer [(Highfinesse-LSA, Germany) ranging from 192 nm to 11000 nm] using different blood samples, having different refractive indices. Each sample has its own refractive index and has independent wavelength shift as shown in fig 5.6. As we performs simulations till now with FDTD algorithm not practically, by assuming that high wt molecules of blood cells replaces the low wt molecules of cancer, subsequently the refractive index of biosensing platform for the two biomarkers (CEA, EGFR) varied respectively. Further, normal blood cells can be easily differentiated from cancerous cell due to CEA and EGFR as they have higher refractive index.

Fig 5.6 shows the resonance wavelength shift with respect to the different refractive indices of unoptimized structure of bio-sensor. To achieve better senstivity without compromising the detection accuracy, the biosensor by varying its different parameters is optimised as discussed above. As illustrated above, sensitivity and detection accuracy have opposite trends but in the proposed bio-sensor both the parameters are achieved an acceptable value for both the cancer bio-markers. As effective refractive index of blood samples is increasing due to Vroman effect, the wavelength effectively shift towards the higher side as shown in fig 5.7 and 5.8. From Fig 5.7, it is understood that biosensor have a

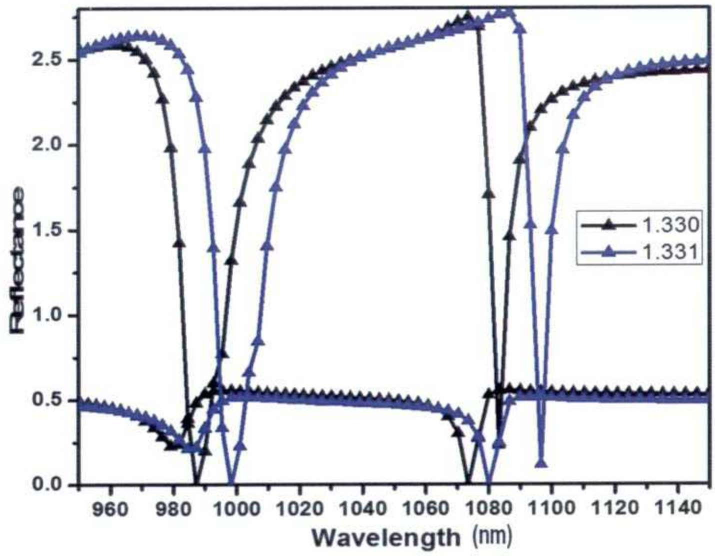

Figure 5.6: Transmission spectra of unoptimzed biosensor for different effective refractive index

narrower curve for CEA biomarkers which is having a refractive index range of 1.32 1.37. It also have a wavelength shift of $\sim 3nm$ for 1.33 and $\sim 13nm$ for 1.34. While fig 5.8 depicted about EGFR biomarkers that shows a wavelength shift of $\sim 18nm$ for 1.66 and $\sim 28nm$ for 1.67. For measuring the performance of biosensor, we have calculated the senstivity S_n and detection accuracy DA for both cancer bio-markers. $S_n \sim 26.91$ and

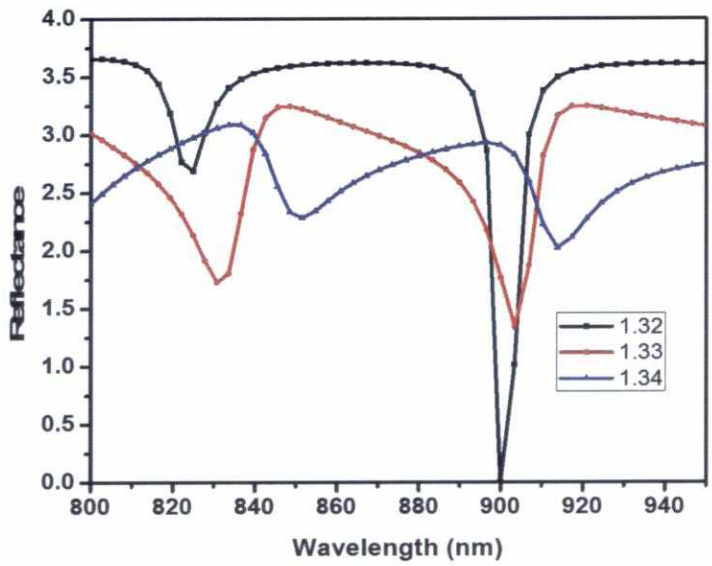

Figure 5.7: Transmission spectra of optimized biosensor for different concentrations of CEA

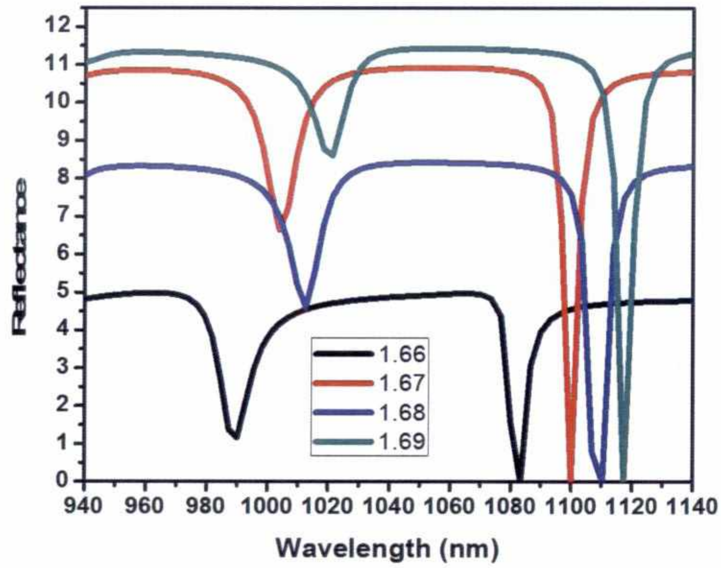

Figure 5.8: Transmission spectra of optimized biosensor for different concentrations of EGFR

$DA \sim 100.18$ at refractive index of ~ 1.33 for CEA as shown in fig 5.9. We also observe a slight increment in DA = 173.15 while $S_n \sim 1349.88$ at refractive index 1.67 as shown in fig 5.10 which proves that high refractive index gains a sharp change in the performance of sensor as compared to [117].

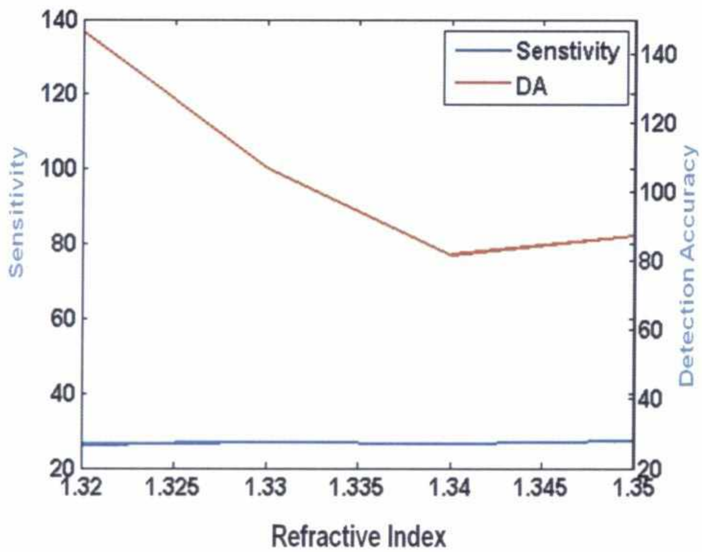

Figure 5.9: Variation of refractive index with sensitivity and detection accuracy for CEA

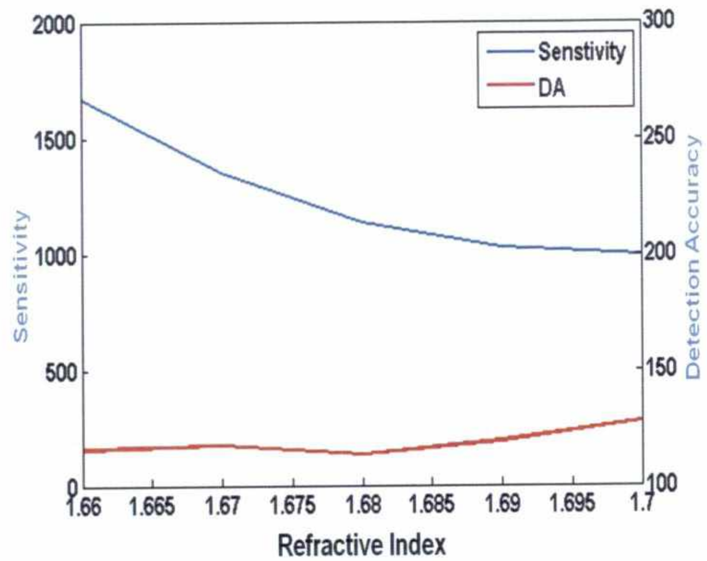

Figure 5.10: Variation of refractive index with sensitivity and detection accuracy for EGFR

5.5 Summary

A multilayer SPR biosensor with gratings has been proposed and optimized with the help of Vroman effect. The said biosensor has been achieved acceptable value of detection accuracy and sensitivity. The Vroman effect curtail the requirement of bio-receptors for the detection of both the lung cancer biomarkers. The presence of TiO_2 makes it more impressive biosensor for better detection of said biomarkers. FDTD method is used for performing the aforesaid detection. The performance of this biosensor is improved by optimizing the grating size and thickness of different metal layers which further results in significant improvement in sensitivity in proportion to the detection accuracy. Proposed bio-sensor can be a promising device to early detection of different cancer biomarkers (i.e. CEA and EGFR).

Chapter 6

Conclusions and Future Works

This chapter is the concluding part of the thesis and also proposes some suggestions towards which the present work can be further extended. Section 6.1 brings out the overall conclusions of the research work carried out in this thesis and in section 6.3 suggestions regarding the future research directions and possible extensions of the work presented in the thesis, are made.

6.1 Conclusion

In this thesis, SPR waveguide sensor with multilayer and gratings presented. The main objective and motivation of current work is to find out the depth contribution of different properties of SPR metals, characteristics, and further optimisation of said sensor has been presented. The presented work mainly focuses on two major areas i.e. senstivity enhancement using multilayer and grating concept and early detection of lung cancer biomarkers. Previously presented/theoretical work has been validated and simulated for different designs with different SPR metals has been simulated and validated with previous presented and theoretical work. The development of multilayer and grating structure has been reviewed. The concept of wave interrogation method for different characteristics of SPR waveguide has also been investigated. The propagation length of SPR waveguide sensor defines the various loss due to imaginary part of SPR metals. Characteristics curves for a particulars wavelength has been obtained for different grating period and metal layer thickness. Different properties of SPR waveguide as a function of grating periods, width, refractive index and metal layer thickness has been investigated. In this work, different guided modes have been investigated using coupled mode theory in chapter 5. It is assumed that guided modes of waveguide have changing effect under weak perturbation effect. Accordingly, slotted MDM waveguide have been presented to obtain high performance. It has further used to quantify extra ordinary transmission using Air in slotted waveguide. A symmetrical MDM waveguide has been simulated with a slot using FDTD method. A comparative study has been carried out in between Silicon-di-oxide and Air as slot with using a metal layer thickness of 100 nm. An air gap of 50 nm in combination with 100 nm thickness of metal layer provides improved results and shows an senstivity of ∼ 1800 nm/RIU at resonance wavelength of ∼ 900 nm. The best feature of the presented waveguide that is its possibility to operate in any spectral region with extra ordinary transmission. Silicon-di-oxide have certain losses in slot that's why it has not shown improved transmission and senstivity at ∼ 10-50 nm.

By combining the multilayer and grating concept, it has been analysed that electric field penetration is very small in substrate due to which weaker interaction of modal fields has been observed. By using various properties of metals, a high performance SPR waveguide sensor has been investigated. A combination of Aluminum (Al) and Gold (Au) has been put in to obtain high resolution using wavelength interrogation method. The utilization of aluminium allows the development of highly sensitive, reproducible and easy to use waveguide sensor. The properties of grating with bi-metallic layer has been investigated for guiding modes. It is demonstrated that multilayer grated SPR waveguide sensor is not just a sensitive sensor but it can also be used for detection for different concentration. The obtained senstivity ∼ 7600 nm/RIU and DA ∼ 230 $\mu m - 1$ for SPR waveguide sensor proves its ability with a gold layer thickness of 10 nm and aluminium of 3 nm. Said design carried an important feature is that sensor showed a high performance against the high refractive index value.

Besides that, a high performance SPR waveguide sensor has been designed in chapter 4 for detection of different chemical concentrations. A comparative study also done in between the aluminium and gold to achieve narrower resonance dip. Depend upon the findings observed earlier, a biosensor with periodic grating with multilayer structure has been demonstrated for detection of lung cancer biomarkers. Acceptable senstivity and detection accuracy has been achieved using this bio-sensing platform. Even a good selectivity has also been obtained using Vroman effect. The presence of gold and gratings both causes a sharp resonance in transmission specturm while the presence of Vroman effect makes it possible for proper detection of cancer biomarkers. FDTD method is used for performing the aforesaid detection. Presence of different cancer bio-markers in blood samples is detected by observing the resonance wavelength in transmission spectrum of proposed bio-sensing platform. The performance of this biosensor is improved by optimizing the grating size and thickness of different metal layers which further results in significant improvement in sensitivity in proportion to the detection accuracy. The reported work is very useful as the proposed biosensor has a good fabrication tolerance and easy to fabricate. Proposed bio-sensor can be a promising device to early detection of different lung cancer biomarkers (i.e. CEA and EGFR).

6.2 Recommendations

1. SPR based high performance sensing can be very beneficial in performing fast and accurate quality checks of different chemicals in water and other environmental monitoring techniques. Nevertheless, both the sensors can also contribute to the food processing and safety and even agriculture also.

2. It is strongly recommended to implement biosensor for early lung cancer detection, using both the said lung cancer biomarkers using Vroman effect for general public health sector. It removes the complex method and time consuming process and most important it is non-invasive method. This kind of sensor provide the major benefit to society directly, as these sensor have the ability to reach the inaccessible places and used without the need of active source (electrical energy) at the sensing location.

3. SPR based sensing platform with Vroman effect provides better sensitivity and selectivity without bio-receptors. By eliminating the need of bio-receptors, it is much easier to reduce the manufacturing cost and improvise the miniaturisation process. Further, they are totally immune to electrostatic and radio frequency interference. They are also known for intrinsic safety and can even be used in any environmental condition. It can also be used for medical diagnostics using different biomarkers such as heart attack biomarkers, allergy markers and hormones markers etc.

4. Further, miniaturisation of SPR bio-sensing platform is also under progress, Array of nano SPR sensor and multiplex detection further ease the method of detection and improve the limit of detection, real time response as well as sensitivity and selectivity.

6.3 Scope for future work

Research is an continuous and iterative procedure. The present work in the thesis suggests the development of high performance SPR based biosensor for lung cancer using Vroman effect with the help of multilayer and gratings. There are several ways to expand the current work. Certain futureworks in this direction are:

1. In future, we will see advancement in better sensitivity and higher detection accuracy with SPR based biosensor. They can also be used to lipid surface components

and high resolution kinetic analysis.

2. Further advancement in SPR technology will bring mobile based SPR sensor platforms which further improve rapid detection of environmental contaminants.

3. In addition to that, better immobilization methods and biorecognition elements also enable real time detection and continuous monitoring of several biological components which will further contribute to public health and protection of local ecosystems.

4. In next 3-5 years, nano-technology in field of SPR bio-sensing will further revolutionise the cancer detection which in turn will improve the cancer diagnosis & prognosis thus improving the cancer patient survival rates.

5. Point of care (POC) testing allows the patient and medical staff to get the cancer diagnostic results rapidly and easily as it is a non-invasive technique. Further, biosensing technology depends upon cancer biomarkers, its further achievement will bring multiple target detection of multiple biomarkers. Devices like POC testing and multi-biosensors technology must maintain the reliability and accuracy of the laboratory.

6. The use of biosensors in cancer monitoring and detection holds vast potential. SPR based biosensor technology has the ability to provide accurate and fast detection. It also provides monitoring of angiogenesis, reliable imaging of cancer cells & cancer metastasis, and the ability to determine the effectiveness of anticancer chemotherapy agents. Biosensors can be designed to detect emerging cancer biomarkers and to determine drug effectiveness at various target sites.

7. Simulation as well as theoretical studies can be done on SPR technology for Photonic Crystal Fiber/waveguide. This is currently being investigated by many research groups, its characterization and optimization can be further carried out for some health and medical diagnostics.

8. We envision that evolution of technology based on SPR biosensor continues and advanced biosensor with new bio-specific surfaces using new binding methods, that will definitely lead to robust SPR biosensing platform. These biosensor further, provide sensitive, rapid and specific detection of chemical and biological species in different analyte which extend benefit to food safety, environmental monitoring and medical diagnostics.

9. Having the features of fast identification, these sensor can be deployed in defense areas where portable, fast and rugged units are required for identification of warfare

agents in the field.

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Multilayer with periodic grating based high performance SPR waveguide sensor

Pradeep Kumar Teotia *, R.S. Kaler

Optical Fiber Communication Research Laboratory (OFCR Lab), ECE Deptt, Thapar University, Patiala 147004, India

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ABSTRACT

We propose a high performance periodic grating coupled multi-layered surface plasmon resonance (SPR) waveguide based on Al+Au. High sensitivity is obtained by using grating filled with silver instead of air. Further sensor's performance is analysed by optimising width and thickness of SPR active metal layer as well as grating period also. Using finite difference time domain (FDTD) method, we have shown that sensitivity and detection accuracy can be improvised using appropriate multi-layered grating configuration.

1. Introduction

In the recent years, optical properties of metallic structures have shown renewed interest. This influence empowers to minimise the structures or dimensions of optical devices, which is becoming probable due to the advancement in the patterning of metals [1,2]. Meanwhile SPR (Surface Plasmon Resonance) based optical sensors have marked their presence due to emerging biosensing application areas. SPR biosensors have been widely explored and several geometries related to SPR configuration have been developed [3,4]. To detect small changes in refractive index, for example that near to metal-dielectric, SPR technology was first introduced. In addition to that, it has several advantages like high sensitivity, fast speed response etc. Previously SPR biosensing technology used the Kretschmann configuration which constituted the prism based implementation of attenuated total reflection [5]. SPR technique is based on the electromagnetic oscillations generated due to free charge density fluctuations which propagate through metal and dielectric interface are known as Surface Plasmon [6]. Recently surface plasmons have gained more interest of researchers as it has the ability to propagate through sub-wavelength sized holes [7]. Multilayered metallic nanostructure is also in focus other than single metallic interface since it has an advantage of using same plasmonic active metals at both ends to obtain structures with improved optical responses [8]. The bi-metallic layered structure has the ability to squeeze the surface plasmon modes in the dielectric region. The improvement in computational techniques for better understanding of plasmonic behaviour in bi-metallic structures and consistent fabrication methods have made it promising to use complex metal structures for various applications [9]. It is worth mentioning that performance of SPR sensor will be determined by dispersion properties of metals [10]. Generally, metals which show dispersion properties and have SPR characteristics like silver (Ag), gold (Au) and aluminium (Al) etc. Further each SPR metal exhibits its own SPR properties, such as aluminium exhibit narrower resonance curve while gold carries better chemical stability and absorption coefficient [3]. Although Al have some issues over chemical stability, so to overcome this issue we have simulated the multilayered grated waveguide of gold and aluminium. West et al. [11] emerged new window for alternate plasmonics materials with the aspects of fabrication. They also represented the comparative study of different type of metals, metal alloys and doped semiconductors. In continuation of that Xiao et al. [12] also stated the theory of enhanced transmission through a gold film with sub wavelength array holes. They emphasised this technology for door opening of surface plasmon based sensors. Jory et al. [13] demonstrated a prototype of SPR sensor with gratings, with angular interrogation method. In continuation to this, Hu et al. [14] also proposed a high performance grating coupled SPR sensor to achieve angular sensitivity of 187.2°/RIU. Srivastava et al. [3] proposed a periodic multilayered SPR waveguide sensor with SPR active metals. Some of them only focused on the angular interrogation which was so complex in optimising and calibration. Moreover, angular interrogation method was not so accurate vide Srivastava et al. [3]. While maintaining a periodic multilayered waveguide is

* Corresponding author.
E-mail address: pradeepkteotia@yahoo.com (P.K. Teotia).

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ARTICLE

Exploitation of Slotted Multilayer Coatings for the Enhancement of Light Transmission and Sensitivity Through Surface Plasmon Resonance Waveguide

Pradeep Teotia* and R. S. Kaler

We propose a metal slotted dielectric waveguide with a high refractive index material in which surface plasmon can propagate. By studying several symmetrical metal dielectric metal structures we have also analysed that slot waveguide geometry also shows many intriguing properties that are not shown in the single interface metal dielectric with the use of high refractive index material. The surface plasmon resonances of slot MDM waveguide are studied using finite difference time domain simulations. The slot MDM waveguide geometry not only exhibit high index sensitivity ($\approx$200 RIU^{-1}) but also shows higher transmission ($\approx$10%). We have also investigated the geometry with different dielectric materials (Air, Silicon-di-Oxide). The transmission obtained is in the given order Au–Si–Air–Au > Au–Si–Au > Au–Si–SiO_2–Au for slot MDM structures.

Keywords: Surface Plasmons, Reflectance, Subwavelength, Negative Refractive Index.

1. INTRODUCTION

In the recent years, optical properties of metallic structures have shown renewed interest. This influence empowers to minimise the structures or dimensions of optical devices, which is becoming probable due to the advancement in the patterning of metals.[1] The electromagnetic oscillations generated due to free charge density fluctuations which propagate through metal and dielectric interface are known as Surface Plasmon.[2] Recently surface plasmon have gained more interest of researchers as it has the ability to propagate through subwavelength sized holes.[3] Multilayer metallic nanostructure is also in focus other than single metallic interface since it has an advantage of using same plasmonic active metals at both ends to obtain structures with improved optical responses.[4] Metal-Dielectric-Metal (MDM) structure has the ability to squeeze the surface plasmon modes in the dielectric region. The improvement in computational techniques for better understanding of plasmonic behaviour in metallic-dielectric-metallic structures and consistent fabrication methods have made it promising to use complex metal structures for various applications.[5] High propagation losses are usually related with surface plasmons due to imaginary part of metal which further accompany losses. Xu et al.[6] fabricated a novel silicon waveguide, capable for confining light in nm-widest structure with a low-refractive-index material. Prade et al.[7] proposed a dielectric slab waveguide with different surrounding of metals along with the core, which was further used for nanometric focusing of light. Feng et al.[8] found that deep-subwavelength-sized with high-index dielectrics and metal structures with slot waveguide was showing a promising future without compromising the overall propagation loss. Allosp et al.[9] investigated the multilayer coating with a combination of Ge–SiO_2–Pt/Ag/Au for different refractive indices in aqueous regime. The above referred studies suggest about the propagation of light through MDM structures made either with different refractive index materials or focusing light for different applications. None of the discussed work refer about the high refractive index materials with multilayer MDM structures that can be used as high performance sensing applications. In line with this, surface plasmons in slot metallic-dielectric-metallic structures have been proposed and studied with different slot material e.g., Air/Silicondioxide with different thickness. A well balanced trade-off between propagation loss and sensitivity as well as propagation length with extra ordinary transmission will be intensively studied. This study emphasizing the mitigation of the problems that are associated

Electronics and Communication Engineering Department, Thapar University, Patiala, 147004
*Author to whom correspondence should be addressed.
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1-D grating based SPR biosensor for the detection of lung cancer biomarkers using Vroman effect

Pradeep Kumar Teotia*, R.S. Kaler

Thapar University, Optical Fiber Communication and Research Lab, Department of Electronics and Communication, Nabha Road, Patiala 147004, India

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A B S T R A C T

Grating based surface plasmon resonance waveguide biosensor have been reported for the detection of lung cancer biomarkers using Vroman effect. The proposed grating based multilayered biosensor is designed with high detection accuracy for Epidermal growth factor receptor (EGFR) and also analysed to show high detection accuracy with acceptable sensitivity for both cancer biomarkers. The introduction of periodic grating with multilayer metals generates a good resonance that make it possible for early detection of cancerous cells. Using finite difference time domain method, it is observed wavelength of biosensor get red-shifted on variations of the refractive index due to the presence of both these cancerous bio-markers. The reported detection accuracy and sensitivity of proposed biosensor is quite acceptable for both lung cancer biomarkers i.e. Carcinoembryonic antigen (CEA) and Epidermal growth factor receptor (EGFR) which further offer us label free early detection of lung cancer using these biomarkers.

1. Introduction

Diseases can be classified as infectious and non-infectious diseases. Non-infectious diseases can be chronic disease and have higher incidence worldwide resulting in rapid death. Asthma, heart disease, kidney disease, cancer etc. are chronic diseases. Cancer can be classified depending on the location of the tissue affected. Lung cancer is one of the type of cancer which is said to be the result of smoking. Lung cancer is mostly diagnosed in the later stages as it is confused with Tuberculosis and COPD diseases of chest. Treatment of lung cancer is a long process and survival rate in India is very less (i.e. almost 5 year) [1]. Present diagnosis methods (biopsy, sputum cytology) which are available are either invasive or too much expensive. Increasing incidence of cancer has enforced us for the development of highly sensitive, precise and real time device for the diagnosis [2] of the disease so that better prognosis can be done. Recently, researchers and scientists have developed fast and inexpensive techniques for the detection of cancer biomarker protein [3] using biosensors, as cancer can be cured if early detected. Biosensor is a device which has the competence to analyse different samples i.e. blood or clinical samples. Recent advances in biosensor technology is leading to miniaturization of sensing devices. Several biomarkers have been identified for detecting the cancer effectively that further categorized to type of cancer. In this manner, Carcinoembryonic antigen (CEA) and Epidermal growth factor receptor (EGFR) have extensively studied as lung cancer biomarkers [4] in terms of diagnosis. CEA and EGFR biomarker is a type of protein and have a certain limit value 3–5 ng/ml and 2–20 μg/ml [5] in our body. According to the prescribed value, both biomarker have a accepted effective refractive index range 1.32–1.37 and 1.66–1.70 [6]. Blood cells contain the above said biomarkers however, cancerous blood cells have higher refractive index than the normal blood cells. Surface plasmon resonance based biosensor have emerged as indispensable tool in the field of biomedical research [6]. Optical SPR based biosensor works on the principle of change in the effective refractive index. Few techniques have been developed with different SPR geometries in field of biosensor area but all present techniques have certain limitations i.e. low stability, lack of antibody diversity etc. In parallel to this, existing biosensor based analysis is very time consuming [7]. Conventional SPR biosensors have a problem of alignment and lacking of experimental precision. These devices are also not so compact [8,9]. Traditional SPR biosensors generally uses glass as core and a single layer of thin metal film for excitation of surface plasmons. The propagation of light in the SPR biosensor can be understood by Maxwell equations [10]. The multilayer structure as defined in our previous work [11] has the ability to cuddle in the adjacent dielectric region and consistent fabrication techniques have made it simple for complex metal layer structures [12,13]. SPR metals have dispersion properties which further exhibit better chemical stability and absorption coefficient. SPR sensors have been demonstrated for detection of pesticide [14], blood sugar [15], breast cancer

* Corresponding author.
E-mail address: pradeepkteotia@yahoo.com (P.K. Teotia).

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