CHAPTER 3

SURFACE PLASMON RESONANCE BASED FIBER OPTIC SENSOR UTILIZING INDIUM OXIDE

3.1 Introduction

As discussed in chapter 2, transparent conducting oxides (TCOs) are of immense interest due to their good electrical conductivity, high transparency in the visible region, and high infrared reflectivity. They form vital mechanism in large number of optoelectronic devices such as light emitting diodes, photodetectors, touch panels, flat panel displays, and solar cells [137,144,145]. In addition, it has become possible to obtain surface plasmon resonance with transparent conducting metal oxide thin films [71]. Recently, indium oxide (In$_2$O$_3$) has been reported to be a better substitute of noble metals (Au and Ag) for producing surface plasmons [146]. Among various TCOs, In$_2$O$_3$ is a potential material for numerous applications such as solar cells and gas sensing due to its highest available transmissivity for visible light combined with lowest electrical resistivity and reflection spectra in IR region [127]. It is an n-type wide band gap semiconductor (band gap ~ 3.7 eV) and has high electrical conductivity. In its stochiometric state, it is insulator and becomes conducting with increasing its oxygen deficiency. Its optical and electrical properties can be considerably modified using suitable doping. Besides it, thin films of In$_2$O$_3$ are continuous (i.e. no agglomeration as islands) and no involvement of band to band transitions.

In this chapter, a SPR based fiber optic sensor with In$_2$O$_3$ layer has been theoretically discussed. The surface plasmon resonance produced by coupling of evanescent light to surface plasmons is used as the sensing scheme. The wavelength interrogation method is exploited for the analysis of SPR based fiber optic sensor. The SPR sensor with In$_2$O$_3$ layer is shown to possess high sensitivity in the near infrared region of spectrum. In addition, the sensitivity of the SPR sensor decreases with increase in the thickness of In$_2$O$_3$ layer. 170 nm thick In$_2$O$_3$ layer based fiber optic SPR sensor shows high sensitivity of 4600 nm/RIU.
3.2 Theory

The SPR sensing is based on the principle of attenuated total reflection (ATR) with Kretschmann configuration. In the proposed SPR based fiber optic sensor, the sensing system consisting of a fiber core-In$_2$O$_3$-sensing medium is considered as shown in Fig. 3.1.

![Figure 3.1: Schematic diagram of SPR based fiber optic sensor with In$_2$O$_3$ layer](image)

The plastic cladding around the core from the middle portion of a step index multimode PCS fiber is removed and is then coated with a thin In$_2$O$_3$ layer. This In$_2$O$_3$ layer is finally surrounded by the sensing medium. The light from a broadband (polychromatic) source is launched into one of the ends of the optical fiber with proper optics and the transmitted light is detected at the other end of the optical fiber.

3.2.1 Layer I (Fiber core)

This layer is made of core of optical fiber. The core of the optical fiber is assumed to be made of fused silica. The refractive index of fused silica varies with wavelength according to Sellmeier dispersion relation as,
\[
n_1(\lambda) = \sqrt{1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2}} \tag{3.1}
\]

Where, \( \lambda \) is the wavelength in \( \mu m \) and \( a_1, a_2, a_3, b_1, b_2 \) and \( b_3 \) are Sellmeier coefficients. The values of these coefficients are given as, \( a_1 = 0.6961663 \), \( a_2 = 0.4079426 \), \( a_3 = 0.8974794 \), \( b_1 = 0.0684043 \mu m \), \( b_2 = 0.1162414 \mu m \) and \( b_3 = 9.896161 \mu m \) [141].

### 3.2.2 Layer II (In\(_2\)O\(_3\) layer)

This layer is made of In\(_2\)O\(_3\). The dielectric constant of In\(_2\)O\(_3\) is written according to Drude model as [128],

\[
\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega/\tau} + \frac{s_0\omega_0^2}{\omega_0^2 - \omega^2 + i\gamma\omega} \tag{3.2}
\]

Here, \( \varepsilon_\infty \) is the high frequency dielectric constant, \( \tau \) is the electronic scattering time, \( \omega_p \) is the plasma frequency, \( s_0 \) is the oscillator strength, \( \omega_0 \) is the oscillator resonance frequency and \( \gamma \) is the damping constant. The parameters used for In\(_2\)O\(_3\) are: \( \varepsilon_\infty = 3.5 \), \( \tau = 1.014 \times 10^{-14} \) s rad\(^{-1} \), \( \omega_p = 1.02 \times 10^{15} \) rad s\(^{-1} \), \( s_0 = 0.7 \), \( \omega_0 = 7.29 \times 10^{15} \) rad s\(^{-1} \) and \( \gamma = 7.08 \times 10^{14} \) rad s\(^{-1} \) [128].

### 3.2.3 Layer III (Sensing medium)

This layer is made of sensing medium. The dielectric constant of the sensing medium is \( \varepsilon_s \). If \( n_s \) is the refractive index of the sensing medium, then \( \varepsilon_s = n_s^2 \). The resonance condition for excitation of surface plasmon wave is given as,

\[
\frac{2\pi}{\lambda} n_s \sin \theta = \text{Re}\{K_{sp}\} \tag{3.3}
\]
Where, \( K_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}} = \frac{2\pi}{\lambda} \sqrt{\frac{\varepsilon_m n_s^2}{\varepsilon_m + n_s^2}} \) is the propagation constant of the surface plasmon wave and \( c \) is the speed of light in vacuum. The left hand side of Eq. (3.3) denotes the propagation constant of the light incident at an angle \( \theta \) and the right hand side shows the real part of propagation constant of the surface plasmon wave.

### 3.2.4 Transmitted Power

The expression for the reflection coefficient (reflectance) of \( p \)-polarized incident light can be obtained by using the matrix method for \( N \)-layer model as mentioned in appendix A. Considering that all the guided rays are launched in the fiber using a collimated source and a microscope objective, the angular power distribution of rays guided in the fiber is given as [18],

\[
dP \propto \frac{n_1^2 \sin \theta \cos \theta}{(1 - n_1^2 \cos^2 \theta)^2} d\theta
\]  

(3.4)

Where, \( \theta \) is the angle of the ray with the normal to the core-cladding interface. Also, \( n_f \) is the refractive index of the core of the fiber. To calculate the effective transmitted power, the reflectance (\( R_p \)) for a single reflection is raised to the power of the number of reflections the specific propagating angle undergoes with the sensor interface. Hence, for \( p \)-polarized light, the generalized expression for the normalized transmitted power in an optical fiber based SPR sensor will be given as,

\[
P_{trans} = \frac{\int_{\theta_0}^{\pi/2} R_p^{\text{s}_f (\theta)} \frac{n_1^2 \sin \theta \cos \theta}{(1 - n_1^2 \cos^2 \theta)^2} d\theta}{\int_{\theta_0}^{\pi/2} n_1^2 \sin \theta \cos \theta}{(1 - n_1^2 \cos^2 \theta)^2} d\theta}
\]  

(3.5)

Where, \( N_{ref} (\theta) = \frac{L}{D \tan \theta} \)  

(3.6)
And, \( \theta_{cr} = \sin^{-1}\left(\frac{n_{cl}}{n_1}\right) \)  

(3.7)

Here, \( N_{ref}(\theta) \) is the total number of reflections performed by a ray making an angle \( \theta \) with the normal to the core-metal layer interface in the sensing region. \( L \) and \( D \) are the length of the exposed sensing region and the fiber core diameter respectively. Also, \( \theta_{cr} \) is the critical angle of the fiber and \( n_{cl} \) is the refractive index of the cladding of the fiber.

### 3.2.5 Sensitivity

Resonance wavelength \( (\lambda_{res}) \) is determined corresponding to the refractive index of the sensing medium \( (n_s) \) in the SPR sensor based on wavelength interrogation. If the refractive index of the sensing medium is altered by \( \delta n_s \), the resonance wavelength shifts by \( \delta \lambda_{res} \). The sensitivity \( (S_n) \) of a SPR sensor with wavelength interrogation is defined as [64],

\[
S_n = \frac{\delta \lambda_{res}}{\delta n_s}
\]

(3.8)

### 3.3 Results and discussion

For numerical calculations, the refractive index of the sensing medium is changed from 1.30 to 1.38 in steps of 0.02 and following values of the parameters have been used:

- Numerical aperture of the fiber = 0.24, fiber core diameter \( D = 600 \mu \text{m} \), length of the exposed sensing region \( L = 15 \text{ mm} \).

To optimize the thickness of \( \text{In}_2\text{O}_3 \) layer, the transmitted output power of SPR based fiber optic sensor have been calculated for various thickness values (170 nm, 220 nm, 270 nm, 320 nm, 370 nm and 420 nm) of \( \text{In}_2\text{O}_3 \) layer. The SPR transmittance curves for different thicknesses of \( \text{In}_2\text{O}_3 \) layer have been plotted in Figs. 3.2 and 3.3.
Figure 3.2: Transmittance curves of SPR based fiber optic sensor for different thickness values of In$_2$O$_3$ layer for refractive index of sensing medium = 1.30

Figure 3.3: Transmittance curves of SPR based fiber optic sensor for different thickness values of In$_2$O$_3$ layer for refractive index of sensing medium = 1.38

Figs. 3.2 and 3.3 show the SPR transmittance curves for six different thickness values i.e. 170 nm, 220 nm, 270 nm, 320 nm, 370 nm and 420 nm of In$_2$O$_3$ layer as the refractive index
of the sensing medium changes from 1.30 to 1.38 (in steps of 0.02). The corresponding resonance wavelengths of SPR sensor for various thicknesses of $\text{In}_2\text{O}_3$ layer are determined and are listed in table 3.1.

**Table 3.1:** Resonance wavelengths of SPR based fiber optic sensor for different values of thickness of $\text{In}_2\text{O}_3$ layer

<table>
<thead>
<tr>
<th>Thickness of $\text{In}_2\text{O}_3$ layer (nm)</th>
<th>Resonance wavelength (nm) for various refractive indices of sensing medium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.30</td>
</tr>
<tr>
<td>170</td>
<td>1545</td>
</tr>
<tr>
<td>220</td>
<td>1810</td>
</tr>
<tr>
<td>270</td>
<td>2000</td>
</tr>
<tr>
<td>320</td>
<td>2140</td>
</tr>
<tr>
<td>370</td>
<td>2240</td>
</tr>
<tr>
<td>420</td>
<td>2315</td>
</tr>
</tbody>
</table>

From table 3.1, it is clear that the resonance wavelength of SPR sensor shifts from 1545 nm to 1915 nm, 1810 nm to 2140 nm, 2000 nm to 2280 nm, 2140 nm to 2370 nm, 2240 nm to 2435 nm and 2315 nm to 2485 nm for 170 nm, 220 nm, 270 nm, 320 nm, 370 nm and 420 nm thick $\text{In}_2\text{O}_3$ layers respectively, as the refractive index of the sensing medium varies from 1.30 to 1.38. Thus, the shift in resonance wavelength of SPR sensor is different for different thicknesses of $\text{In}_2\text{O}_3$ layer. The shift in resonance wavelength of the SPR sensor is maximum for 170 nm thick $\text{In}_2\text{O}_3$ layer and minimum for 420 nm thick $\text{In}_2\text{O}_3$ layer. Also, the shift in resonance wavelength of SPR sensor decreases as the thickness of $\text{In}_2\text{O}_3$ layer is increased gradually. The variations of resonance wavelength of SPR sensor with refractive index of sensing medium for different thicknesses of $\text{In}_2\text{O}_3$ layer have been plotted in Fig. 3.4.
Figure 3.4: Variations of resonance wavelength of the SPR based fiber optic sensor with refractive index of sensing medium for different thickness values of In$_2$O$_3$ layer

Fig. 3.4 illustrates the plots of resonance wavelength of SPR sensor with refractive index of sensing medium for various thickness values i.e. 170 nm, 220 nm, 270 nm, 320 nm, 370 nm and 420 nm of In$_2$O$_3$ layer. The resonance wavelength of SPR sensor for different thicknesses of In$_2$O$_3$ layer increases linearly with increase in refractive index of the sensing medium. The variations of resonance wavelength with refractive index of the sensing medium for all thicknesses of In$_2$O$_3$ layer follow the same suit. The slope of resonance wavelength over the refractive index for 170 nm thick In$_2$O$_3$ layer is highest while it is least for 420 nm thick In$_2$O$_3$ layer. However, the slopes of resonance wavelength over the refractive index for other thickness values (220 nm, 270 nm, 320 nm and 370 nm) of In$_2$O$_3$ layer are larger than that of 420 nm thick In$_2$O$_3$ layer and are smaller than that of 170 nm thick In$_2$O$_3$ layer. Nevertheless, the shifts in resonance wavelength for all these cases are nearly linear over the whole range of refractive indices (i.e. 1.30 to 1.38) of the sensing medium.
To obtain the maximum sensitivity of the SPR sensor, it will be essential to identify the optimized thickness of In$_2$O$_3$ layer. The sensitivity of the SPR based fiber optic sensor for various thicknesses of In$_2$O$_3$ layer are compared in table 3.2.

**Table 3.2:** Sensitivity of SPR based fiber optic sensor for different values of thickness of In$_2$O$_3$ layer

<table>
<thead>
<tr>
<th>Thickness of In$_2$O$_3$ layer (nm)</th>
<th>Sensitivity $S_a$ (nm/RIU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>4600</td>
</tr>
<tr>
<td>220</td>
<td>4100</td>
</tr>
<tr>
<td>270</td>
<td>3475</td>
</tr>
<tr>
<td>320</td>
<td>2875</td>
</tr>
<tr>
<td>370</td>
<td>2425</td>
</tr>
<tr>
<td>420</td>
<td>2100</td>
</tr>
</tbody>
</table>

It can be seen from table 3.2, that the sensitivity of 170 nm thick In$_2$O$_3$ layer based SPR sensor is maximum (4600 nm/RIU) and it is minimum (2100 nm/RIU) for 420 nm thick In$_2$O$_3$ layer based SPR sensor. Though, the sensitivities of SPR sensor for other thicknesses (220 nm, 270 nm, 320 nm and 370 nm) of In$_2$O$_3$ layer are intermediate between those of 170 nm and 420 nm thick In$_2$O$_3$ layers. The variations of sensitivity of the SPR sensor with thickness of In$_2$O$_3$ layer have been plotted in Fig. 3.5.
Fig. 3.5 depicts the variation of sensitivity of the SPR sensor with thickness of In$_2$O$_3$ layer. It is noticeable that the sensitivity of the SPR sensor decreases as the thickness of In$_2$O$_3$ layer increases. This happens because the thick In$_2$O$_3$ layer permits less interaction between surface plasmon mode and the fiber mode, resulting in small absorption of light power by the sensing medium around resonance wavelength. This causes increased normalized transmitted power and hence decreases the sensitivity of the sensor. Further, it can be observed from Fig. 3.5 and table 3.2 that 170 nm thick In$_2$O$_3$ layer based SPR sensor has the highest sensitivity (4600 nm/RIU). Therefore, in designing SPR based fiber optic sensor with high sensitivity, the proper thickness of In$_2$O$_3$ layer should be chosen. However, the optimized thickness of In$_2$O$_3$ layer of the SPR based fiber optic sensor is found to be 170 nm. So, taking all these facts into consideration, it is concluded that 170 nm thick In$_2$O$_3$ layer based fiber optic SPR sensor demonstrates high sensitivity of 4600 nm/RIU.
3.4 Conclusions

The simulation of a SPR based fiber optic sensor with In$_2$O$_3$ layer has been presented. The sensitivity of SPR sensor for various thicknesses (170 nm to 420 nm) of In$_2$O$_3$ layer is studied theoretically. The proposed In$_2$O$_3$ layer based SPR sensor possesses high sensitivity with resonance dip in near infrared region of spectrum allowing the sensing in infrared spectral region, which needs attention to many environmental and security applications. In addition, the sensitivity of the SPR sensor decreases with increase in thickness of In$_2$O$_3$ layer. 170 nm thick In$_2$O$_3$ layer based fiber optic SPR sensor displays high sensitivity of 4600 nm/RIU.