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Optical Fiber Surface Plasmon Sensor: Theoretical Approach to Detect Viral Aerosols

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Abstract

The rapid and precise detection of viral aerosol has received considerable attention to prevent airborne diseases. In these days, coronavirus disease and its detection has become a common subject in the worldwide. The study is proposed to the detection of viral aerosol by surface plasmon resonance techniques. In this paper, design and optimization of a surface plasmon resonance sensor based on polymer optical fiber for detection of noval coronavirus is theoretically presented and validated. Here, S-glycoprotein antigen is considered as the marker of covid. The dependency of resonance wavelength of surface plasmon sensor on numerical aperture and refractive index of optical fiber is obtained using ray approach. It is observed that low refractive index core and high numerical aperture of optical fiber waveguide provides the better performance to the detection of viral aerosol. The propagation wavelength, propagation length, penetration depth in metal and aqueous media are also calculated and found 1.475 μm, 81.046 μm, 0.2672 μm, 2.059 μm respectively at 2.0 μm incident wavelength.

Keywords: Polymer fiber • Surface plasmon resonance sensor • Viral aerosol • Sensitivity

Introduction

The study of viral aerosols has enormously explored area because of their unrecognized importance and unresolved technical challenges. Now days, tropospheric aerosols have growing interest due to the exposure of different bacteria and viruses. The viral and bacterial concentration with their ratio in different environment like costal arctic ocean, coastal pacific ocean, lake, agricultural soil, forest soil, human gut, air etc. estimated by a group of researchers [1]. The airborne viruses i.e. acute respiratory syndrome, influenza, rhino, corona, adeno, respiratory syncytial, entero and noroviruses etc. Identified and prone to carry by aerosol [2]. The aerosols are classified in the term of their mass concentration, particle number concentration and particle size distribution and it was found that sub-micrometer sized aerosols have the largest contribution to viral diseases like bronchiolitis, asthama, lung cancer, pneumonia, croup damage etc [3]. The retention of removal viral aerosols by different filters i.e. nano fiber filter, glass fiber filter, PTFE filter and alumina nanofiber filter has been studied by the authors [4]. These airborne viruses spread out quickly and it is observed that SARS-COV-2 virus affected almost 127 billion people followed by 2.8 million deaths [5] therefore a rapid, precise and real-time detection of different viral aerosol is the demand of present scenario. However, surface plasmon resonance (SPR) technology which serves label free and real time detection of ligand-analyte immobilization at the sensing surface and may be a suitable candidate for such detection [6]. Literatures suggest that the viral surrogate MS2 bacteriophage, Influenza-A virus is detected by SPR sensor [7-8]. In SPR sensor a glass substrate coated with thin film of metal is used to measure the changes in refractive index (RI) of the sensor surface [9]. Now in present covid pandemic this SPR technology is growing interest to detect the SARS-COV-2 virus. Theoretically approach for detection of S-glycoprotein based on antigen- antibody interaction principle is presented by the researches [10-11]. It is also found that SPR technique is capable to the detection of sub-micron sized aerosol that can be operated on real-time measurement. Therefore, in present communication the detection of sub-micron sized viral aerosol loaded with corona virus is presented through surface plasmon resonance sensor.

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Research

Theory and design consideration

The schematic diagram of proposed optical fiber sensor is shown in Figure 1. The present model consists of an optical fiber in which small part are decaled and coated with a thin layer of silver metal. This coated fiber is placed in a chamber which sniffs sub-micron sized viral aerosol. Light passes into one end of the fiber by through light source and detected by the optical spectrum analyzer through its second end. The dielectric constant of the metal is given as [12],

$$\varepsilon_m(\lambda) = 1 - \frac{\lambda^2 \lambda_c}{\lambda_p^2(\lambda_c + i\lambda)} \tag{1}$$

Where λ_p = 1.6826 × 10^{-7} m is plasma wavelength and λ_c = 8.9342 × 10^{-6} m collision wavelength. Surface plasmons are generated due to charge density oscillations at the metal and dielectric interface and the associated wave is called the Surface Plasmon Wave (SPW). The surface plasmon wave vector ($\boldsymbol{k}_{spp}$) and incident wave vector(k) is given as [13]

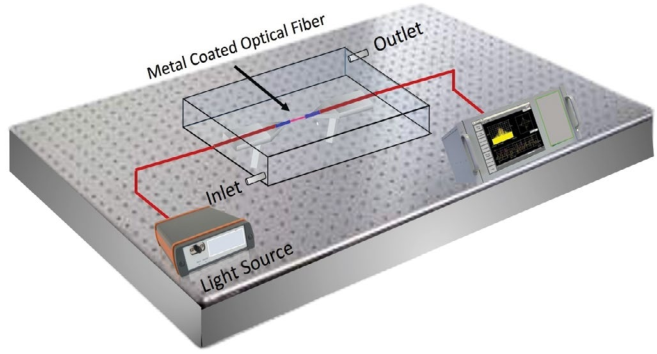

Figure 1. Schematic diagram of optical fiber SPR sensor.

$$k_{spp} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}} \tag{2}$$

$$k = \frac{2\pi}{\lambda}\sqrt{\varepsilon_f}\sin\theta \tag{3}$$

Where ε_f, ε_m and ε_d are dielectric constant of core of fiber, metal and the analyte respectively. λ and θ denote the wavelength and angle of incident light. The SPR occurs when the wave vector of incident light and SPW is matches at particular wavelength. At fixed incident angle, this wavelength is known as the resonance wavelength (λ_{res}). Since metal has the complex RI, the real (k'_{spp}) and imaginary (k''_{spp}) wave vector of surface plasmon wave is as fellow [14]

$$k'_{spp} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m+\varepsilon_d}} \tag{4}$$

$$k''_{spp} = \frac{2\pi}{\lambda}\frac{\varepsilon''_m}{2(\varepsilon')^2}\left(\frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m+\varepsilon_d}\right)^{3/2} \tag{5}$$

Where ε'_m and ε''_m are the real and imaginary dielectric of the metal. The characteristics of surface plasmon wave is describes in the term of surface plasmon wavelength (λ_{spp}) and surface plasmon propagation Length (δ_{SPP}). These each term represents the real ($\lambda_{spp}=2\pi/k'_{spp}$) and imaginary part ($\delta_{SPPP}=1/2k''_{spp}$) of the SPW and expressed as

$$\lambda_{spp} = \lambda_0\sqrt{\frac{\varepsilon'_m+\varepsilon_d}{\varepsilon'_m \varepsilon_d}} \tag{6}$$

$$\delta_{SPP} = \frac{\lambda}{2\pi}\frac{(\varepsilon'_m)^2}{\varepsilon''_m}\left(\frac{\varepsilon'_m+\varepsilon_d}{\varepsilon'_m \varepsilon_d}\right)^{3/2} \tag{7}$$

The field associated with SPW decays exponentially in the perpendicular direction of both the media. This relation of surface plasmon penetration depth in dielectric (δ_d) and metal (δ_m) is expressed as

$$\delta_d = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'_m+\varepsilon_d}{(\varepsilon_d)^2}} \tag{8}$$

$$\delta_m = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'_m+\varepsilon_d}{(\varepsilon'_m)^2}} \tag{9}$$

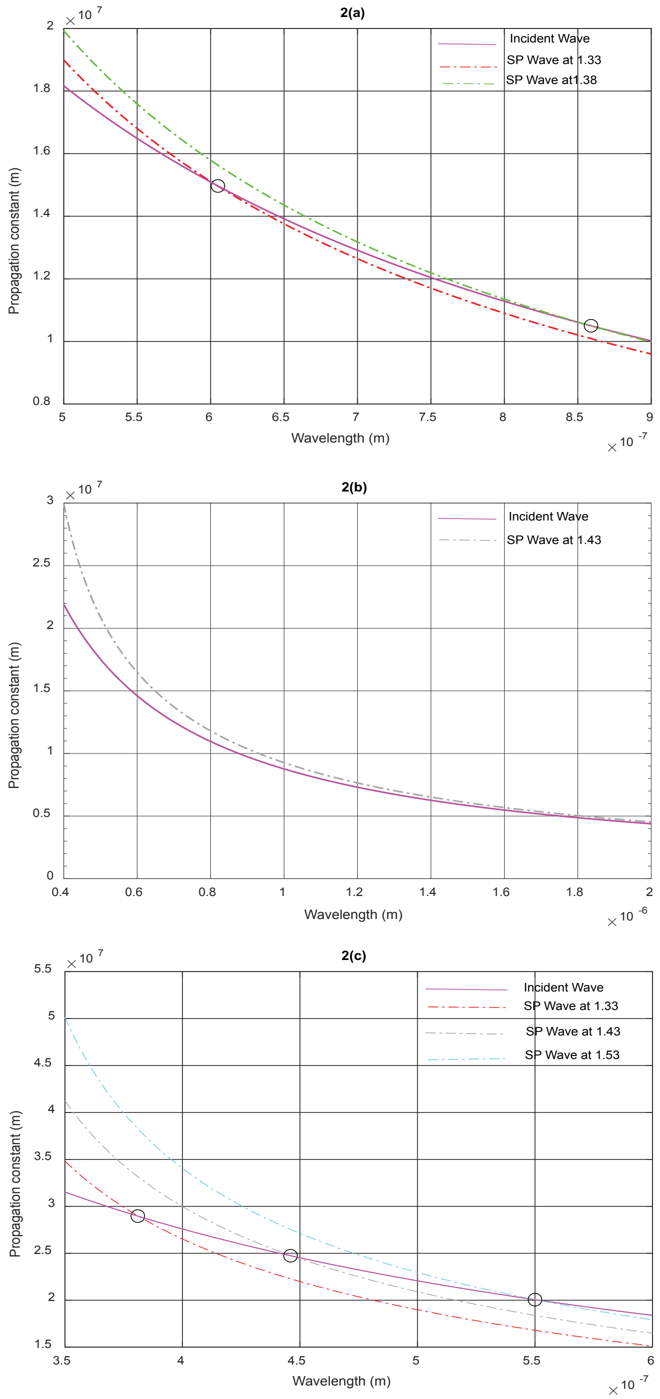

Figure 2. Propagation constant at different wavelength (a-c).

Results and Discussion

To compute the resonance wavelength, standard fused silica optical fiber having 0.22 numerical apertures and RI 1.457 coated with silver of thickness 50nm is considered. Figure 2a shows the variation of propagation constant with wavelength at fixed angle of incidence. The propagation constant for incident wave and surface plasmon wave at two cover RIs 1.33 red and 1.38 green is plotted. Here the propagation constant of incident light and surface plasmon wave matched at a particular wavelength i.e. 6.05 × 10^{-7} m and 8.59 × 10^{-7} m respectively. Since the change in resonance wavelength with cover RI is known as sensitivity therefore the calculated sensitivity is obtained 5.08 µm/RIU. Figure 2b shows the calculated propagation constant of SPW having high cover material RI i.e. 1.43 (gray). It is noted that incident wave and SPW does not matched to the considered wavelength region. Therefore, there is a limitation to sensing the cover RI by using the standard fused silica fiber. To remove this difficulty, the fiber core being the high refractive index of the material likes SF-10. The calculated propagation constant for incident wave and SPW at three cover RIs 1.33 (red), 1.43 (gray) and 1.53 (Cyan) is shown in Figure 2c. Here the computed sensitivity is achieved 0.66 µm/RIU and 1.03 µm/RIU. It is observed that due to increases the core RI, the cover sensing RI is extended. Therefore, the material of fiber is vital role of detection the viral aerosol. To the study the viral aerosol of sub-micron size, the different material of fiber core i.e. fused silica, BK7, BAF10, SF10, LASF9, Si_3N_4, Ta_2O_5 and their respective RI 1.457, 1.515, 1.667, 1.778, 1.845, 2.02, 2.10 is considered [15,16]. Using these core materials RI and 0.22 NA the calculated sensitivity and related fitted curve are shown in Figure 3a the calculated sensitivities are varying from 3.33 µm/RIU to 0.320 µm/RIU for the detection of S- glycoprotein in a phosphate-buffered saline (PBS) solution. Here, the cover RI is assessed as, n_d=1.3348+ Δn, where 1.3348 and Δn(0.012) are the RI of PBS and fluctuating RI due to the different concentration of ligand-analyte interaction [10-11]. It is also clear that, sensitivity decreases by increasing the core RI of fiber. The variation of sensitivity is exhibit at different NA in Figure 3b as far as the plasmonic condition is fulfilled for fused silica optical fiber. It is noted that the obtained sensitivity is varying from 3.33 µm/RIU to 34.49 µm/RIU. It is observed that low RI and high NA of the fiber provides the better performance to detection of covid loaded viral aerosol but low RI of the fiber not layout a range to detection to cover RI. Nowadays, high NA polymer based optical fibers are easily available in the market [17]. This PMMA fiber has higher core RI 1.49 and 0.60 NA. The propagation constant of this PMMA fiber is calculated and shown in Figure 4. The attained sensitivity of this fiber is 28.08 μm/RIU for the detection of S-glycoprotein in PBS solution. The variations of propagation wavelength and propagation length with different wavelength of the incident light are shown in Figure 5a and 5b. Similarly, the penetration depth in metal and cover media at different incident wavelength are calculated and plotted in Figure 6a and 6b. It is observed that by increasing the wavelength of incident light, the propagation wavelength, propagation length, penetration depth in metal and aqueous media increases. The obtained propagation wavelength, propagation length, penetration depth in metal and aqueous media at different incident wavelength 0.5 μm, 1μm 1.5 μm and 2 μm are tabulated in Table 1. It is observed that the

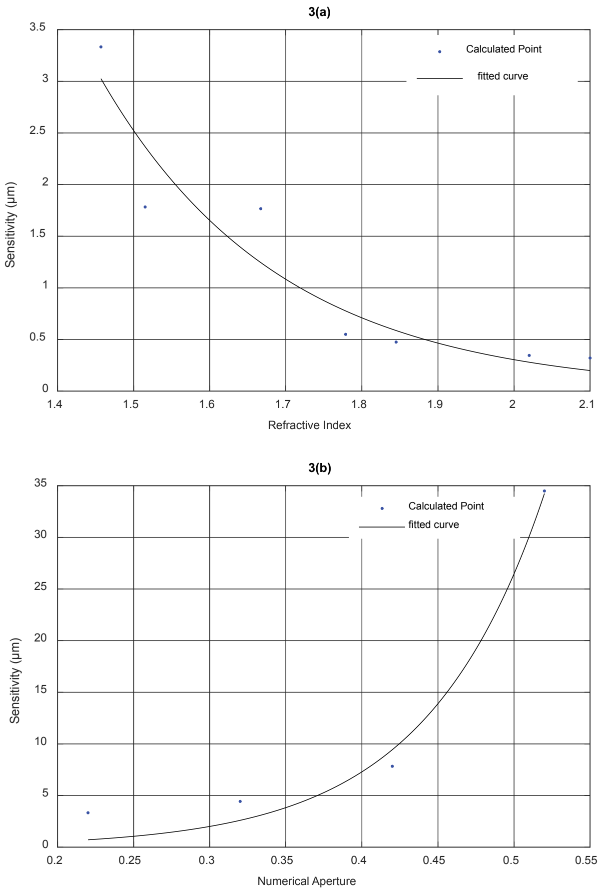

Figure 3. Sensitivity at different core refractive index (a) and numerical aperture (b).

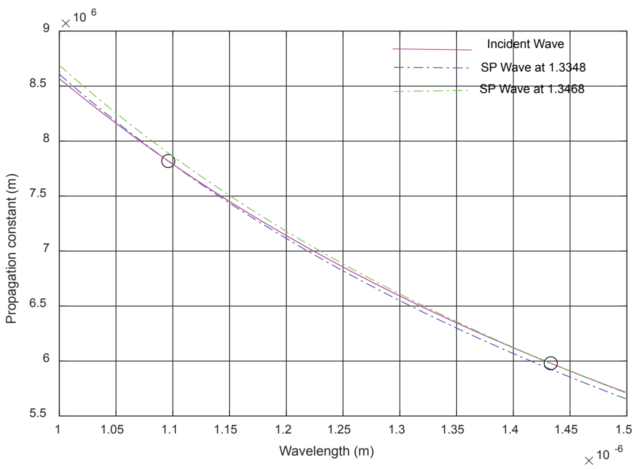

Figure 4. Propagation constant at different wavelength.

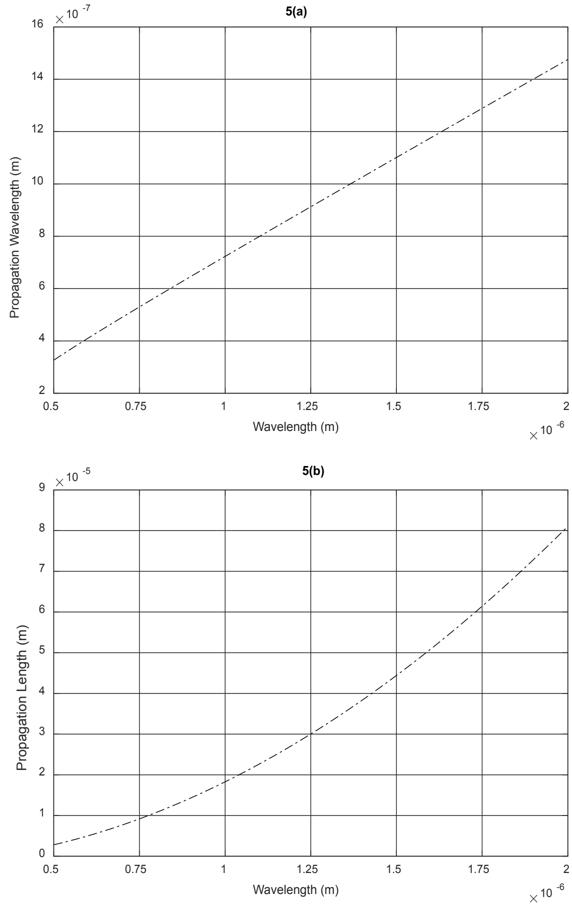

Figure 5. Propagation wavelength (a) and propagation length at different wavelength (b).

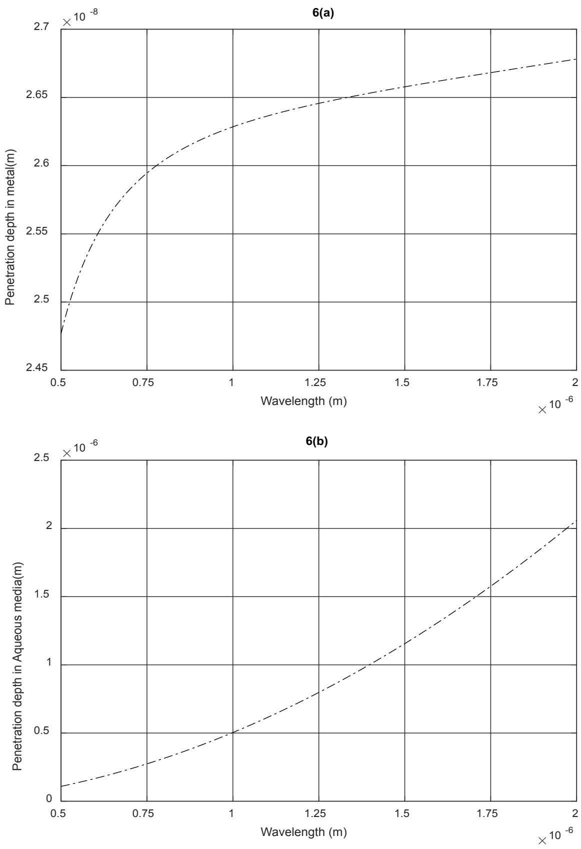

Figure 6. Penetration depth in metal (a) and aqueous media (b) at different wavelength.

Table 1. SPR sensor parameter at different wavelength.

Incident Wavelength (µm)	Propagation Wavelength (µm)	Propagation Length (µm)	Penetration Depth in Cover Media (µm)	Penetration Depth in Metal (µm)
0.5 µm	0.326	2.813	0.109	0.024
1.0 µm	0.723	18.279	0.503	0.026
1.5 µm	1.101	44.411	1.155	0.265
2.0 µm	1.475	81.046	2.059	0.267

propagation wavelength and penetration length have remarkable variation to the detection of viral aerosol. The increase in penetration depth in cover media indicates that the fields penetrate in deep with the increase of wavelength. The penetration depth in metal is approximately independent of the wavelength.

Conclusion

Optical fiber SPR sensors open the new possibilities for development of viral aerosol monitoring system. In proposed sensor, it is concluding that high sensitivity is achieved at low refractive index and high numerical aperture of the fiber. But low RI of the fiber not yields a range to detection to high cover RI. Proposed PMMA optical fiber based SPR sensor is able to achieve the sensitivity 28.08 µm/RIU for the detection of S-glycoprotein in PBS solution. The Surface plasmon parameters in the terms of propagation wavelength, propagation length, penetration depth in cover and metal are also calculated at different incident wavelength. The proposed optical fiber SPR sensor may serves as a portable real-time aerosol monitor that can be applied to detection of viral pathogen infectious to humans or animals.

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Statements and Declaration

The author has no conflicts of interest to declare that are relevant to the content of this article.

Conflict of Interest

None.

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