International Journal of Engineering & Technology, 7 (4.30) (2018) 194-199

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Designing of 3D Sensor Chamber for Plasmonic-based Toxic Sensor Detection

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Abstract

Plasmonic sensor implementing an optical phenomenon called Localized Surface Plasmon Resonance (LSPR) resulting from the interaction of free electron with electromagnetic field of light at the metal nanoparticles surface. In this study, the plasmonic sensor has been developed for toxic detection in solution form. This system consists of five components which are the light source, duplex fiber optic, sensor chamber, spectrometer and computer. The sensor chamber has been specially designed using SolidWork software and printed using 3D printer with polylactic acid (PLA) material. The sensing activity was done in the sensor chamber with a sliding drawer which is used to place the sensing material or sample. OceanView software was used to analyze the recorded spectrum from the spectrometer. For this project, the experiment of the plasmonic sensor was carried out using targeted analyte namely chlorpyrifos with deionized (DI) water was set as a reference medium. Gold nanoparticles with nanospheres shape used as sensing materials. The sensing parameters are based on changing its intensity and resonance peak position. This plasmonic sensor was compared with UV-VIS spectrometer data to make sure it standardize and function correctly. Besides, the sensing process toward different concentrations of chlorpyrifos from 7.15 mM to 28.60 mM have been done. As a conclusion, the plasmonic sensor was successfully developed for toxic detection in solution form.

Keywords: *Gold Nanoparticles; Localized Surface Plasmon Resonance (LSPR);Plasmonic Sensor.*

1. Introduction

Localized Surface Plasmon Resonance (LSPR) or known as plasmonic has been chosen as sensing method in many applications due to fast and sensitive response towards targeted analyte. This method applications are used in medical diagnostics, environmental monitoring and food safety [1,2]. The execution of LSPR is widely used in sensor application because of its responsibility to dielectric and refractive index of surrounding medium [3]. The phenomenon of LSPR causing from the interaction of light with noble metal nanoparticles produces a collective oscillation of conduction band electrons [4]. Only materials with a small positive imaginary dielectric constant and negative real such as gold and silver are capable of encouraging surface plasmons. The resonance condition is met when the incident electromagnetic field matches that of the oscillating electrons on the surface of the nanoparticle. Some of sensing applications implementing LSPR such as the detection of formalin liquid [5] and boric acid solution [6] use gold nanosphere as theirs sensing material. Besides, the plasmonic sensor has been used to detect the biological for cancer cell and disease in medical field [7]. Plasmonic sensor also use air as a surrounding medium to detect a toxic gaseous namely sulfur hexafluoride (SF6) and carbon monoxide (CO) [8].

This paper reports a development of plasmonic sensor for toxic detection using gold nanoparticles as its sensing material. This plasmonic sensor setup starting with designing the sensor chamber which is the main part of this system. The sensor chamber has been designed using SolidWork software and printed using 3D printer with polylactic acid (PLA) material. The sensing activity was done in the sensor chamber with a sliding drawer which is used to place the sensing material or sample. Previously, the chamber was made using the mechanical machine with large dimension. The weakness during developing this chamber is hard to modify and constraints to machine scale dimension [9]. Overall, this system consists of five components which are the light source, duplex fiber optic, sensor chamber, spectrometer and computer.

In this study, the insecticide toxic namely chlorpyrifos has been used as targeted analyte. This chemical is used to control many different kinds of pests including termites, mosquitoes, and fire ants. Products with chlorpyrifos are used in agriculture for feeding and food crops also in cattle ear tags. The products containing chlorpyrifos are also used to treat wood fences and utility poles. Chlorpyrifos can be dangerous if it is eaten, inhaled or touched. Chlorpyrifos works by depriving an enzyme which controls messages that travel between nerve cells. It affects the nervous system of people, pets and other animals the same way it affects the target pest [10].

2. Development of plasmonic-based toxic sensor detection

The project was divided into three main phases which are (1) Designing and printing the sensor chamber (2) Setup the plasmonic sensor system and (3) Testing the sensor towards targeted analyte.

2.1. Designing and printing the sensor chamber

2.1.1. Design a sensor chamber

A sensor chamber is a platform to place a sensing material. The sensor chamber was designed using SolidWork software. Then it was printed using 3D printer with polylactic acid (PLA) material. The dimension of the chamber size is 40mm x 50mm x 60mm. The chamber has two holes on the top which to place the fiber optic probe and route for target analyte. The chamber must be stable to prevent any vibration during testing. The sensor chamber consists of two parts which are housing and drawer. All design were in millimetre (mm). The details drawing for each parts are explained below;

Housing

Figure 1, Figure 2 and Figure 3 show the view of the housing design. The function of the housing is to place the drawer and the fiber optic probe. The hole (A) is for placing the drawer (refer to Figure 1).

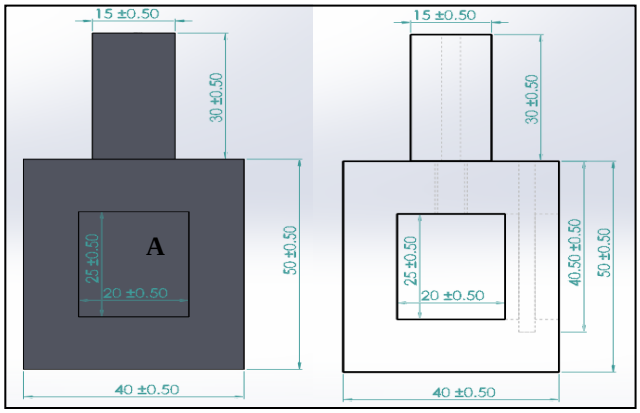

Fig. 1: Front view of housing

The hole (B) is for placing the fiber optic probe (refer to Figure 2). C is refer to a hole for target analyte route.

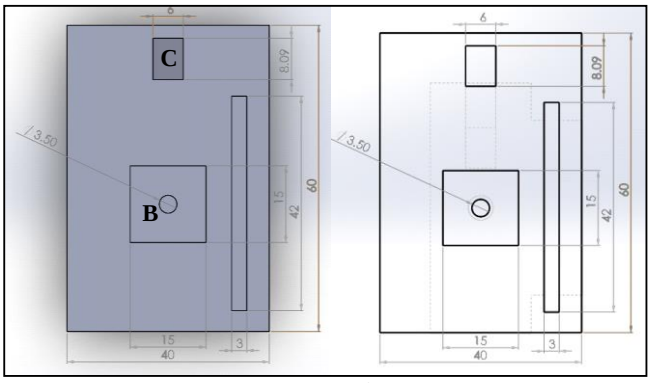

Fig. 2: Top view of housing

The hole (D) is the place to ensure the fiber optic probe and target analyte are properly inserted. After that, the hole (D) will be covered by black plane before the sensing activity carried out (refer to Figure 3).

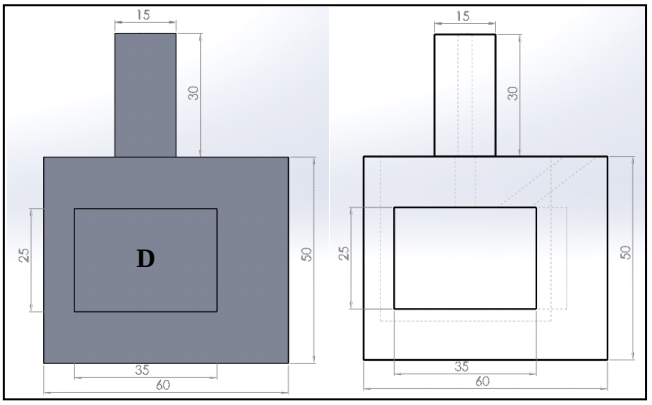

Fig. 3: Side view of housing

Drawer

Figure 4, Figure 5 and Figure 6 show the view of the drawer design. The function of the drawer is to place the sensing material and the targeted analyte.

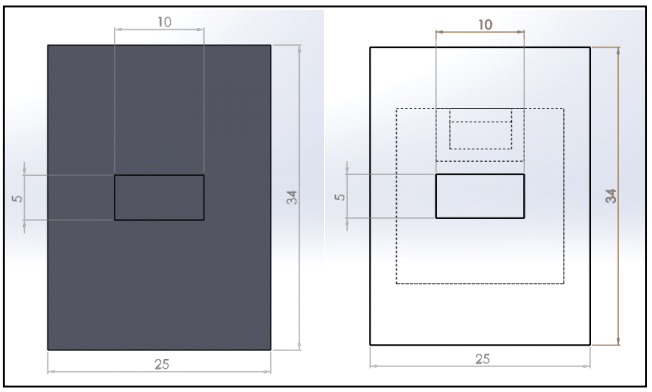

Fig. 4: Front view of drawer

Inside the drawer, there are two holes (C) (see Figure 2) and (E). The hole (C) is a route for target analyte while hole (E) for placing the sensing material.

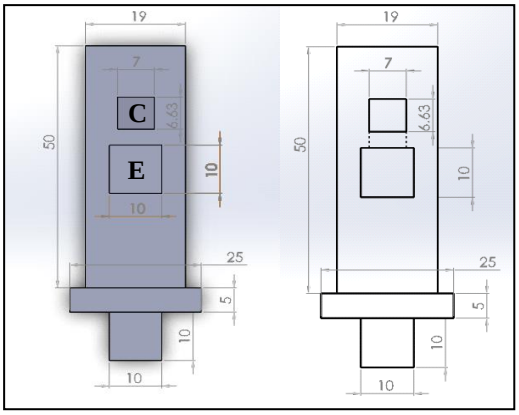

Fig. 5: Top view of drawer

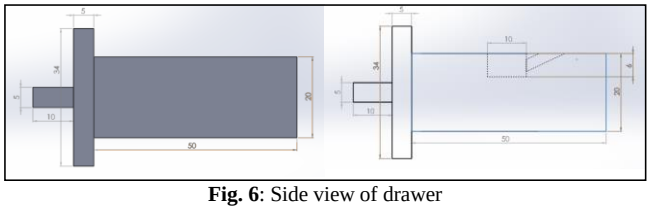

Fig. 6: Side view of drawer

Full view of sensor chamber

Figure 7, Figure 8 and Figure 9 show the view of the sensor chamber design with combination of the housing and drawer. The

drawer can be sliding inside the housing to facilitate the cleaning process of the analyte inside the drawer.

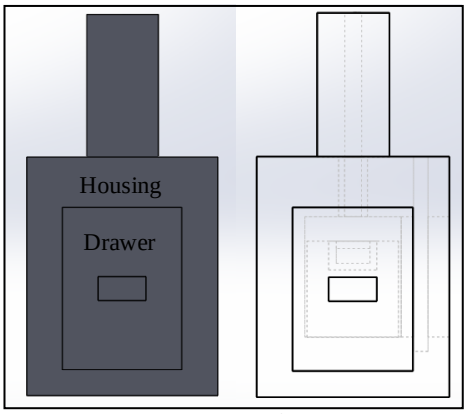

Fig. 7: Front view of chamber

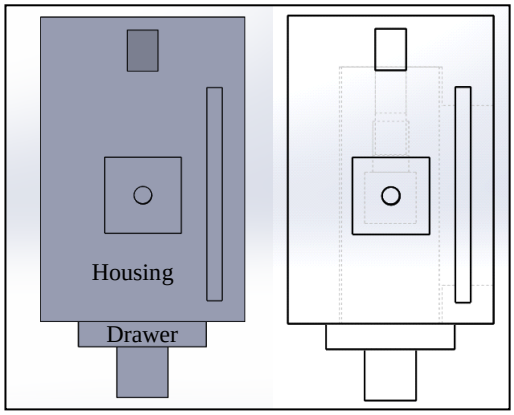

Fig. 8: Top view of chamber

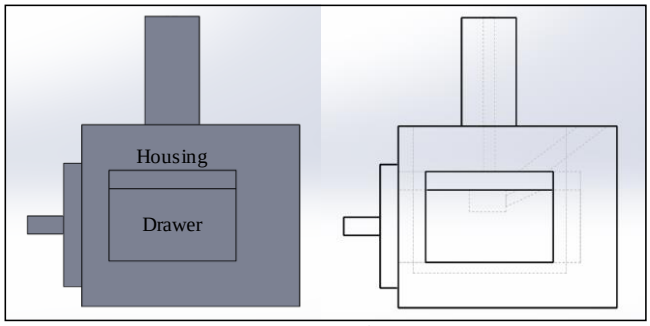

Fig. 9: Side view of chamber

2.1.2. Printing the sensor chamber

The sensor chamber was printed with white PLA material using 3D Printer (Brand). The printing process takes about three hours to print the overall chamber. The weight of the sensor chamber is around sixty grams. At the base of sensor chamber, perspex plate has been added to make the chamber become heavier and stable. Figure 10 and Figure 11 show the sensor chamber that has been printed by 3D printer.

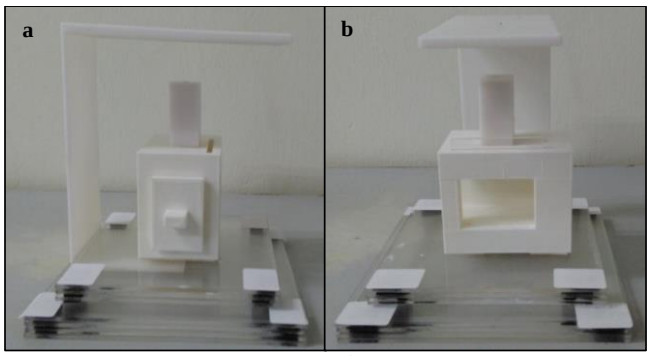

Fig. 10: Sensor chamber (a) front view (b) side view

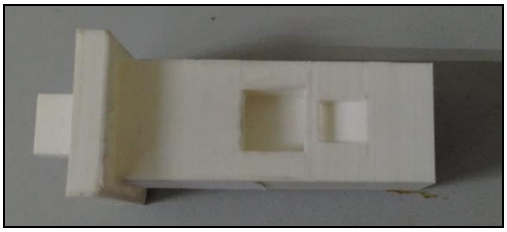

Fig. 11: Drawer of sensor chamber

2.2. Setup the plasmonic sensor system

The sensor system has been setup as shown in Figure 12. The gold nanoparticles substrate was firstly placed at the sensor drawer inside the chamber. From the diagram, light from a light source was connected to the duplex fiber optic probe. The sensor probe or ferrule was positioned approximately 2.5 cm above perpendicular to the targeted analyte. The refractive index and the reflected signal were captured by a spectrometer which was connected to the another fiber optic probe. The signal produced could be displayed and monitored by a computer connected to the spectrometer. Therefore, the recorded light spectrum came from the scattered light of the gold nanoparticles was recorded using spectrometer. The plasmonic sensitivity property were studied by acquiring the optical absorption of the gold nanoparticles in the presence of chlorpyrifos with respective concentrations.

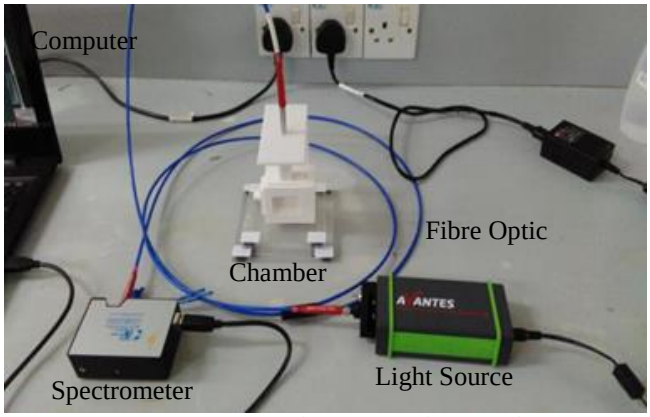

Fig. 12: Sensor setup for detection of chlorpyrifos

As shown in Figure 12, the sensor system consists of five components which are light source, sensor chamber, duplex fiber optic, spectrometer and computer. The following describes the function of each components in this sensor system:

2.2.1. Light source

The light source that supply electromagnetic radiation visible light to stimulate the resonance properties of gold nanoparticles. It used from tungsten halogen lamp which it can emit visible light and near infrared radiation. This project used the light source from Avantes AvaLight-HAL-Mini model. It is a packed and stabilized

halogen light source with changeable focusing of the fiber connection and maximizing output power at the required wavelength. The changeable focus helps to get the most out of the light source which makes sure all possible power is transmitted through the optical fiber [11]. Figure 13 shows the light source from Avantes.

Fig. 13: Light source from Avantes

2.2.2. Duplex fiber optic

The duplex fiber optic acts as a medium for transmit the light source to the sample inside the sensor chamber. After that, the reflected light has been sent from sample to spectrometer. This fiber optic model from Ocean Optics, has 600 µm core probes advance with a 3.18 mm diameter ferrule that can even be used to stimulate and sense fluorescence from solid samples. The fiber optic is 6-around-1 fiber bundle design which the 6 fiber leg connects to light source and the single fiber leg connects to spectrometer for best execution [12]. Figure 14 shows the duplex fiber optic and its probes and ferrule.

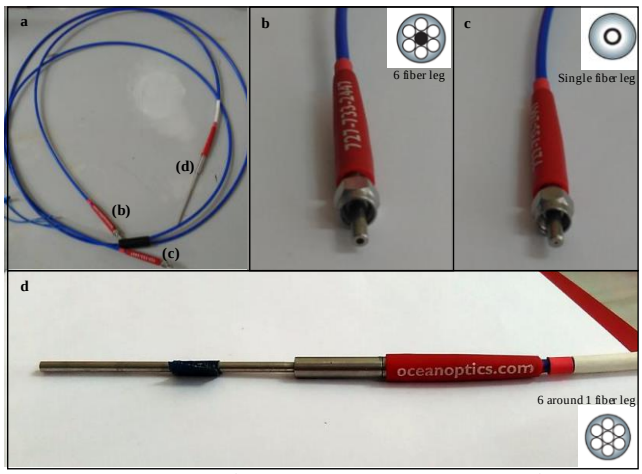

Fig. 14: (a) Duplex fiber optic and its (b, c) probes, (d) ferrule

2.2.3. Sensor chamber

The sensor chamber as shown in Figure 15 is a platform to place the gold nanoparticles for sensing material and the ferrule of duplex fiber optic. As aforementioned before, the sensor chamber has been designed using SolidWork software. Then it was printed using 3D printer with polylactic acid (PLA) material. 3D printing is an additional manufacturing process that builds a three dimensional object from a digital file [13]. The range of the chamber size is 40 mm x 50 mm x 60 mm. The chamber has two holes on top for placing route of the fiber optic and toxic solution. Besides, the chamber is anti-vibration and stable. The sensor chamber and its drawer have been shown in previous section (Figure 10 and 11).

2.2.4. Spectrometer

The spectrometer was used to record the reflected light spectrum by the sample that passed through the fiber optic. This project used spectrometer USB2000 model from Ocean Optics. The function of this spectrometer is to capture light and change it into its spectral forms. Then the signal digitized as a function of wavelength and analyze through a computer. The reflected light through a fiber optic cable into the spectrometer through a narrow aperture known as an entrance slit. The slit vignettes the light as it gets into the spectrometer [14]. Figure 15 shows the spectrometer from Ocean Optic.

Fig. 15: Spectrometer from Ocean Optics

2.2.5. Computer

The computer act as the data collection from the spectrometer to analyze the sample spectrum by using OceanView software. The software allows three types of measurement modes namely absorption, reflection and transmission as previously stated in part of OceanView software. In this study, the absorption mode was chosen as the measurement mode.

2.3. Testing the sensor towards chlorpyrifos

For this project, gold nanospherical have been chosen as a sensing material. The gold nanospherical are synthesized using Seed Mediated Growth Method (SMGM) which is able to produce anisotropic nanoparticles in high yield and structural purity with varying size, shape, structure, composition, and surface chemistry [15,16]. A field emission scanning electron microscopy (FESEM) from Joel JSM-7600F Schottky (USA) was employed to characterize the morphology of the gold nanospherical [17]. Figure 16 show (a) FESEM image of gold nanospherical and (b) gold nanospherical on substrate that has been used in this study.

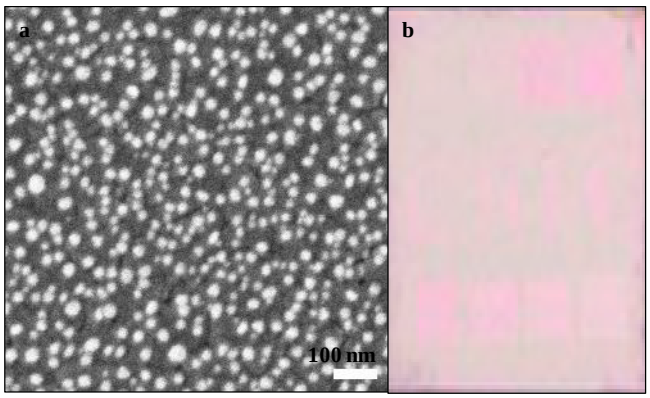

Fig.16: (a) FESEM image of gold nanospherical and (b) gold nanospherical on substrate [9].

The result for this project is done by analysing the graph produced from the plasmonic sensor. This plasmonic sensor used gold nanoparticles which is nanospherical as sensing material with response in air and DI water as reference medium. After that, the plasmonic sensor was used to detect the targeted analyte namely chlorpyrifos. Figure 17 and Figure 18 show the spectrum produce for the sample in air and DI water. While the Table 1 shows the wavelength and peak position of the spectrum for air and DI water detection from the sensor.

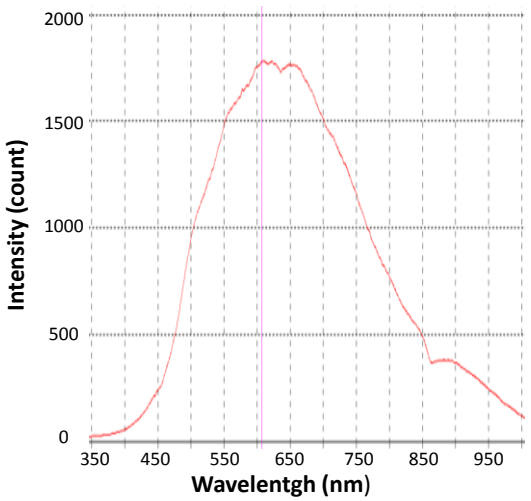

Fig.17: Spectrum of sample with air medium

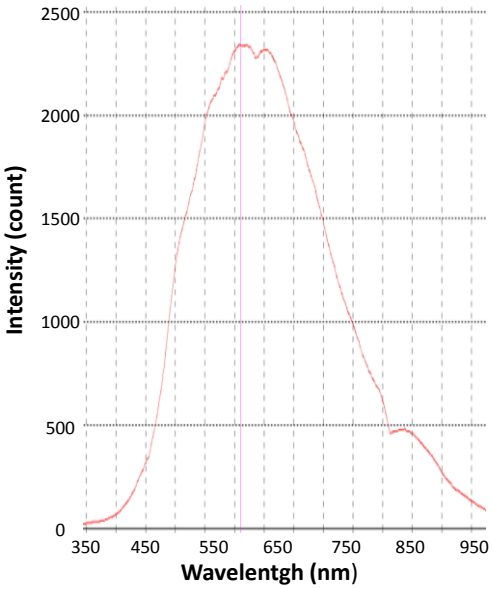

Fig.18: Spectrum of sample with DI water medium

Table 1: Sensor response in air and DI water medium

Medium	Wavelength (nm)	Intensity (a.u) – Peak position
Air	607.50	1775.53
DI water	610.66	2333.15

From the test results, it shows that the test of gold nanoparticles sample in air are 607.50 nm wavelength and peak position of intensity at 1775.53 a.u. While the test of gold nanoparticles sample with DI water have obtained 610.66 nm wavelength and peak position of intensity at 2333.15 a.u. The wavelength and peak position of DI water is higher than air. The test shows that the sensor was function correctly by detecting different medium. This results was coincided with the theory that refractive index for air is 1.0 while refractive index for water is 1.33, higher than water [18]. Then, the plasmonic sensor was used to detect the targeted analyte namely chlorpyrifos with DI water as a reference. For this test, the chlorpyrifos solution was diluted with DI water in different quantities to produce different concentrations from 7.15mM to 28.60mM. The wavelength and peak position as the sensing parameters were recorded and analyzed. Figure 19 shows all the obtained spectrum for the detection of targeted analyte.

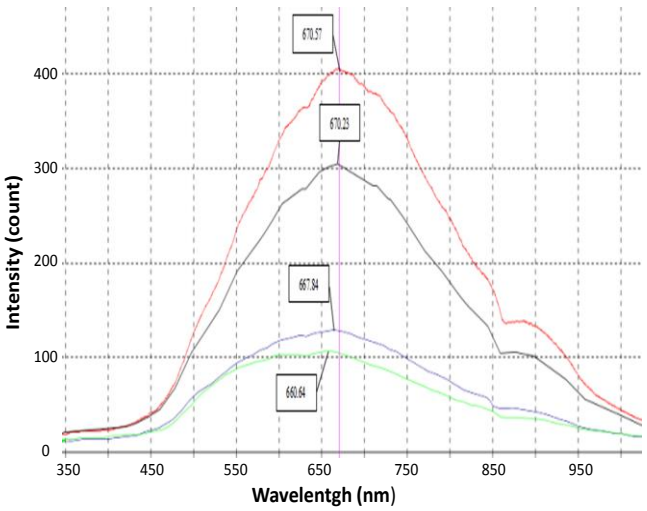

Fig. 19: Sensor responses for all concentrations of chlorpyrifos

Table 2: Sample toward different concentration of chlorpyrifos.

Chlorpyrifos (ml)	DI water (ml)	Dilute concentration (mM)	Wavelength (nm)	Peak position Intensity (a.u)
0.5	50	28.60	660.64	112.76
	100	14.30	667.84	137.31
	150	9.53	670.23	304.44
	200	7.15	670.57	403.88

By comparing data form Table 1 (DI water) and Table 2 (variation of chlorpyrifos), it shows that the presence of chlorpyrifos toxic in DI water was detected by plasmonic sensor. This can be proved by the changes of wavelength and the peak position of the spectrum which are right-shifted. Besides, the wavelength and peak position were increased when the concentrations of chlorpyrifos increase. The results were matched with the fact that the refractive index of chlorpyrifos which is higher than air and water ~1.57 [19].

3. Conclusion

Overall, the plasmonic sensor was successful developed for detection of toxic in solution form. The sensor chamber have been designed and printed using 3D printer. Besides, the sensor system which consist of light source, duplex fiber optic, sensor chamber spectrometer and computer had been setup properly and well functioned. The sensor with gold nanospherical as its sensing material is sensitive toward the presence of targeted analyte namely chlorpyrifos from 7.15 mM to 28.60 mM.
The sensing parameters are supported on changing of their intensity and resonance peak position. One key challenge is to increase the sensitivity of the sensor and improve the limit of detection of desired analyte.

Acknowledgement

This work was supported by Universiti Tun Hussein Onn Malaysia under UTHM Contract Research Grant (U565-UTHM). The author would like to thank to Microelectronics & Nanotechnology - Shamsuddin Research Centre (MiNT-SRC) for the laboratory facilities and Mrs. Elfa Rizan Binti Rizon for her help performing the 3D printing.

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