The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 22, Pages 127-134

ICBASET 2023: International Conference on Basic Sciences, Engineering and Technology

A Study of U-Shaped Optical Fiber Sensor for Sensing Different Concentrations of Glucose and Ion liquid ($HgCl_2$) and a Fabrication of Microfluidics System

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Abstract: In this study, we demonstrate the sensitivity of U-shaped with the different resolutions of Glucose and Mercury Chloride ($HgCl_2$). We also indicate the process of fabricating a Microfluidics system by using CO_2 laser with Poly Methyl Methacrylate (PMMA) as material. According to the experiments, the sensor can be used to evaluate the concentrations of Glucose and $HgCl_2$. While the shift of resonance wavelength raised with the increase of Glucose Concentration from 5% to 50% with R^2=0.95, there is a fluctuation in the shift of resonance wavelength with $HgCl_2$ Concentration from 5 ppm to 50 ppm. Especially with transmission loss, Glucose, and $HgCl_2$ witness the same phenomenon when the transmission loss goes up simultaneously with the increase of concentration, with R^2=0.86 for Glucose and R^2=0.78 for $HgCl_2$. Finally, we manufacture successfully the Microfluidics system with the dimensions including depth: 0.3 mm and width: 0.2 mm. By mixing Glucose 0% and 50%, it leads to the conclusion that the Microfluidics system works appropriately.

Keywords: U-shaped optical fiber sensor, Microfluidics system, CO2 laser.

Introduction

Nowadays, the usages of Optical fiber have expanded not only from optical transmission waveguides in telecommunications (Milner & Chynoweth, 1979) but also to a wide range of applications, including monitoring temperatures (Roriz et al., 2020), mechanical strain (Tregubov et al., 2016), refractive index (RI) (Park et al., 2013), pressure (Ribeiro et al., 2012) and sensing concentrations of liquids and gas (Krohn, MacDougall & Mendez, 2014). Among different types of biosensors, the optical-fiber sensor is one of the best choices because of its simplicity and low-cost operation. However, there are still some disadvantages to this kind of sensor, such as installation and erection issues. In order to improve these issues, there are various types of sensors appeared, including U-shaped sensors (Tan & Stoddart, 2021). By the evanescent wave penetration depth enhancement which results in increasing the sensitivity compared with straight OF.

In recent years, a Lab-on-a-chip is a miniaturized device that integrates into a single chip one or several analyses, usually done in a laboratory. The miniaturization of biochemical operations typically handled in a laboratory has numerous advantages, such as cost efficiency, parallelization, ergonomics, diagnostic speed, and sensitivity. The emergence of the lab-on-a-chip field mainly relies on two core technologies: microfluidics and molecular biology (Bruus, 2008). Microfluidics has made significant advances in the field of biomedical diagnostic research through the development of miniaturized microfluidic and nanofluidic biosensors (Ward & Fan, 2015; Tiwari, Baht & Mahato, 2020).

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

In this study, we will utilize a U-shaped optical fiber sensor to sense the different resolutions of Glucose and $HgCl_2$ then we will use a CO_2 laser to fabricate by directly cutting microfluidic channels from Poly Methyl Methacrylate (PMMA) sheets then assembling together by using Thermal Pressing Techniques. Finally, we use a Microfluidics system to mix different concentrations of Glucose and then evaluating the mixing liquid's concentration with an Abbe refractometer.

Principle of U-shaped Optical Fiber Sensor and Microfluidics System

Principle of U-shaped Optical Fiber Sensor

In the weak-guidance approximation (Renner, 1992) the transverse field distribution in the bent fiber obeys the two-dimensional scalar equation

$$\nabla_t^2\psi(x,y)+\left[k^2 n_{eff}^2(x,y)-\beta^2\right]\psi(x,y)=0 \tag{1}$$

Where, $k=2\pi/\lambda$, λ and β are the wavelength and the complex propagation constant of the leaky mode, respectively.

$$n_{eff}^2(x,y)=n^2(x,y)(1+2x/R) \tag{2}$$

n_{eff}^2 is the squared effective refractive-index distribution in the bent fiber and $n(x,y)$ is the refractive-index distribution in the straight fiber with R as the effective bend radius. Figure 1 demonstrates the cross-section of the optical fiber when being coated by a substance with a refractive index in the cladding and the coating are n_2 and n_3, the radius of the core and the cladding are a and b.

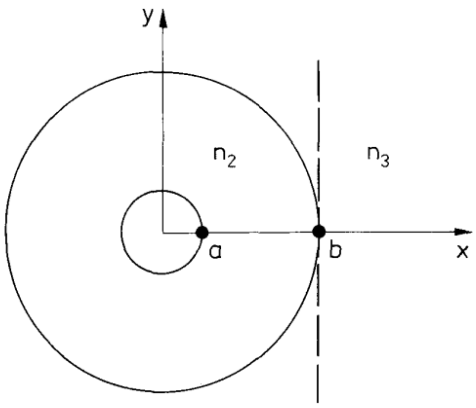


Figure 1. Geometric refractive-index distribution of the coating outside

The loss due to the fiber curvature and the presence of the coating can be obtained from the imaginary part of beta so it is necessary to calculate the change of the propagation constant with respect to its (real) value β_0 in the straight fiber with infinitely extending cladding. The basic idea of the present analysis is to approximate the curved cladding/coating boundary by a plane interface of the same index step with $x=b$. The outwards-radiating field of the leaky fundamental mode in the bent fiber has a purely Gaussian lateral $(y-)$ dependence $\exp\left\{-y^2/\mathrm{w}(x)^2\right\}$ with x-dependent $1/e$ field width of

$$\mathrm{w}(x)=2(x/\gamma)^{1/2}$$

$$\gamma=\left(\beta_0^2-k^2n_2^2\right)^{\frac{1}{2}} \tag{3}$$

The actual cladding/coating interface is described by the circle $x^2 + y^2 = b^2$. If the x-coordinate, at which the trajectory of the beam width intersects the cladding/coating boundary.

$$b^2 = x_T^2 + w(x_T)^2 = x_T^2 + 4x_T / \gamma \quad (4)$$

With the theory of bending transmissions loss from a single-mode fiber with an outer coating, the amount of change between the bending radius of the fiber and the wavelength can be calculated by the formula:

$$\Delta R = \frac{3\pi R}{\gamma b(2 + R_C / R)[(R_C / R) - 1]^{\frac{1}{2}}} \approx \frac{3\lambda}{2n_2}\left(\frac{R^3}{2b^3}\right)^{\frac{1}{2}} \quad (5)$$

$$\Delta\lambda = \frac{3\pi\lambda}{2\gamma b\left(\frac{R_C}{R} - 1\right)^{\frac{1}{2}}\left[1 - \frac{R_C}{R}\left(1 + \frac{3}{\gamma^2 \bar{\varpi}^2}\right)\right]} \approx \frac{3\lambda^2}{4n_2^2}\left(\frac{R}{2b^3}\right)^{\frac{1}{2}} \quad (6)$$

Microfluidics Fundamental Theories

Density is the most significant metric for describing a liquid and its movement. (ρ), pressure (P), and viscosity (η). The density of a liquid is defined as mass (m) per unit volume (v) in units (kg / m^3) (Castillo Leon & Svendsen, 2015).

$$\rho = \frac{m}{v} \quad (7)$$

In closed microfluidics systems, the pressure of a liquid is not important at all because it is only affected by depth; however, in open microfluidics systems, a pressure difference caused by an external source will affect how the liquid moves through the system. Pressure (P) is the ratio of force applied (F) to the area (A) over which that force is distributed in unit kg/ms^2, often referred to as Pascal (Pa).

$$P = \frac{F}{A} \quad (8)$$

The Reynolds number, which is a dimensionless number that can be used to define the kind of flow that is anticipated in the system, can be obtained by taking the ratio of the inertial forces to the viscous forces.

$$\mathrm{Re} = \frac{\rho d v}{\eta} = \frac{dv}{v} \quad (9)$$

In this equation d is the system's typical length scale, which typically includes the smallest dimension or the diameter of tubes and v is the average velocity of the moving liquid.

Simulation, Experiment, and Fabrication

The fabrication of a U-Shaped Optical Fiber Sensor and the Set-up of the Experiment

Figure 2 shows the process of manufacturing a U-shaped sensor. Initially, using the ceramic mold for shaping the sensor, after that, using the heat treatment with the temperature can be seen in TABLE I. Secondly, we utilize UV glue to fix it on the glass plate, finally, using a 3D-printer jig to keep the sensor when conducting experiments to sense different concentrations of Glucose and $HgCl_2$. For each concentration of Glucose and $HgCl_2$, we restart the experiment by cleaning the liquid container with Deionized water (DI water) then drying it with Nitrogen (N_2 gas); the sensor is cleaned by immersing in DI water after that, softly touching KIMTECH wipers for drying.

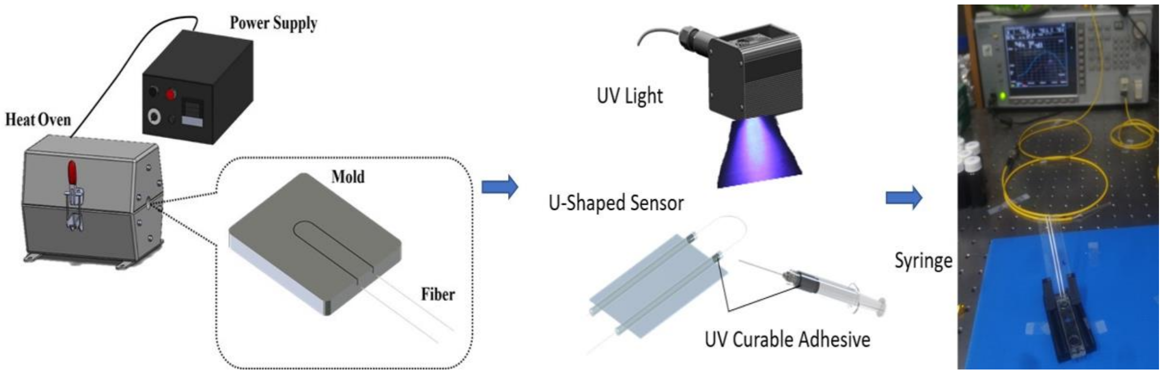


Figure 2. The process of manufacturing the sensor and the set-up of the experiment

Table 1. The temperature of sensor fabrication

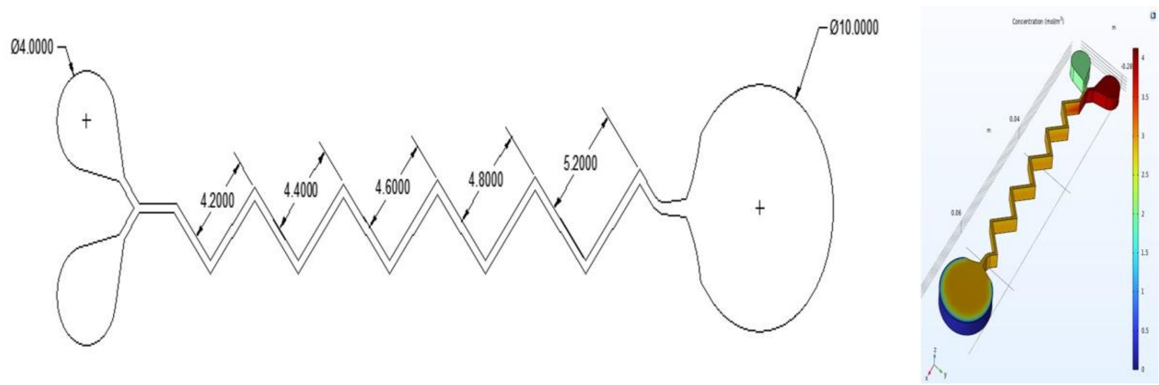
Stage	Temperature (degree Celsius)	Time (Minutes)
Stage 1	600	25
Stage 2	900	40
Stage 3	900	35
Stage 4	600	40
Stage 5	600	25
Stage 6	400	30
Stage 7	400	25
Stage 8	200	30

The simulation of the Microfluidics system

As shown in Figure 3(a), the Microfluidics channels are designed with an overall length of 45 mm, depth of 0.3 mm, and a width of the channel is 0.2 mm with the angle of each channel 45°. Moreover, the length of each channel is increased gradually in order to extend the time that liquid flows inside. We begin the simulation by setting the initial liquid concentrations for each inlet as 2 mol/m^3 and 4 mol/m^3. After flowing inside the system as seen in Figure 3(b), we can easily see the final mixing liquid at the outlet achieving a good result with 3-mol/m^3 concentration spreading over.

The Fabrication of the Microfluidics System

Figure 4 indicates the process of manufacturing a Microfluidics system by using PMMA. Firstly, we use the FLUX Beambox Pro 50W to cut three parts of the Microfluidics system with the middle part is 0.3 mm and the upper and bottom parts is 2 mm. After that, we clean all parts with alcohol before using Thermal Pressing machine to assemble these parts together with temperature: 150 $^{\circ}C$ and the pressure : 80 Kg.



(a) (b)

Figure 3. (a) 2D drawing (b) COMSOL Simulation

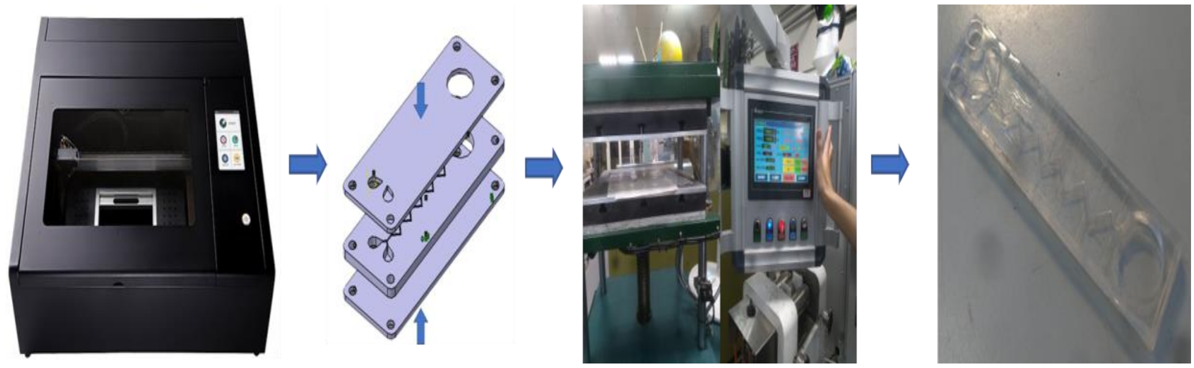


Figure 4. The process of manufacturing microfluidics system

Results and Discussions

Results of Experiments of Sensing Different Concentrations of Glucose and $HgCl_2$

Figure 5 illustrates the overall signal of U-Shaped sensor when sensing the different concentration of Glucose (from 5% to 50%). It is easily seen that at the range of 1620 nm to 1630 nm, there is a significant shift happening not only with the wavelength but also with the transmission. This is a reason why we can consider this signal as the main one when sensing glucose. In order to understand the signal, we will analyze the linear graph of this range in Figure 6.

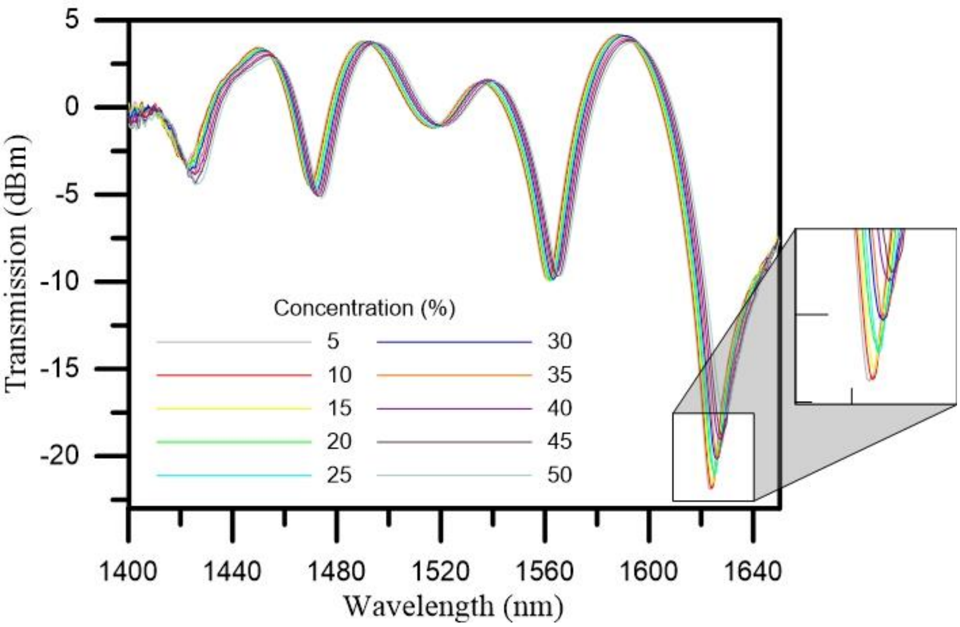


Figure 5. The signal of U-Shaped sensor with Glucose

As seen in Figure 6, in a range of 1620 to 1630, when the concentrations of Glucose rise from 5% to 50%, the resonance wavelength also raises from 1623 nm at 5% to 1629 nm at 50% with R^2= 0.95. The transmission also shares the same trend with wavelength; when the concentrations increase, the dip of the signal increases from -22 dBm at 0% to -17.7 dBm at 50% with R^2=0.86. Compared with the overall signal in Figure 5, we can see that the dip of the signal shift to the right and goes up when the concentration increases.

Figure 7 demonstrates the signal of U-Shaped sensor with $HgCl_2$. As seen in the figure, in a range from 1540 nm to 1550 nm, there is a significant change of the signal when the concentrations of $HgCl_2$ changing from 5 ppm to 50 ppm. Figure 8 depicts the detail of the U-Shaped sensor signal in a range from 1540 nm to 1550 nm. As seen from the figure, while the transmission witnesses an upward trend when the transmission slightly grows from -23.25 dBm at 5 ppm and 10 ppm to -22.9 dBm at 50 ppm, there is a fluctuation of wavelength when changing the concentration of $HgCl_2$. The wavelength declines softly from 1548.7 nm to 1548.5 nm when the concentration at 5 ppm to 20 ppm. After that when increasing the concentrations to 35ppm, the wavelength put up to 1548.85 nm before fluctuating at 1548.6 nm and 1549.3 nm when the concentrations are 40 ppm and 45 ppm. Finally, the wavelength stays at 1549.05 nm when the concentration is 50 ppm. From the explanation above, there is no room for doubt that the R^2 of wavelength is smaller significantly than that of the transmission, 0.43 compared with 0.78.

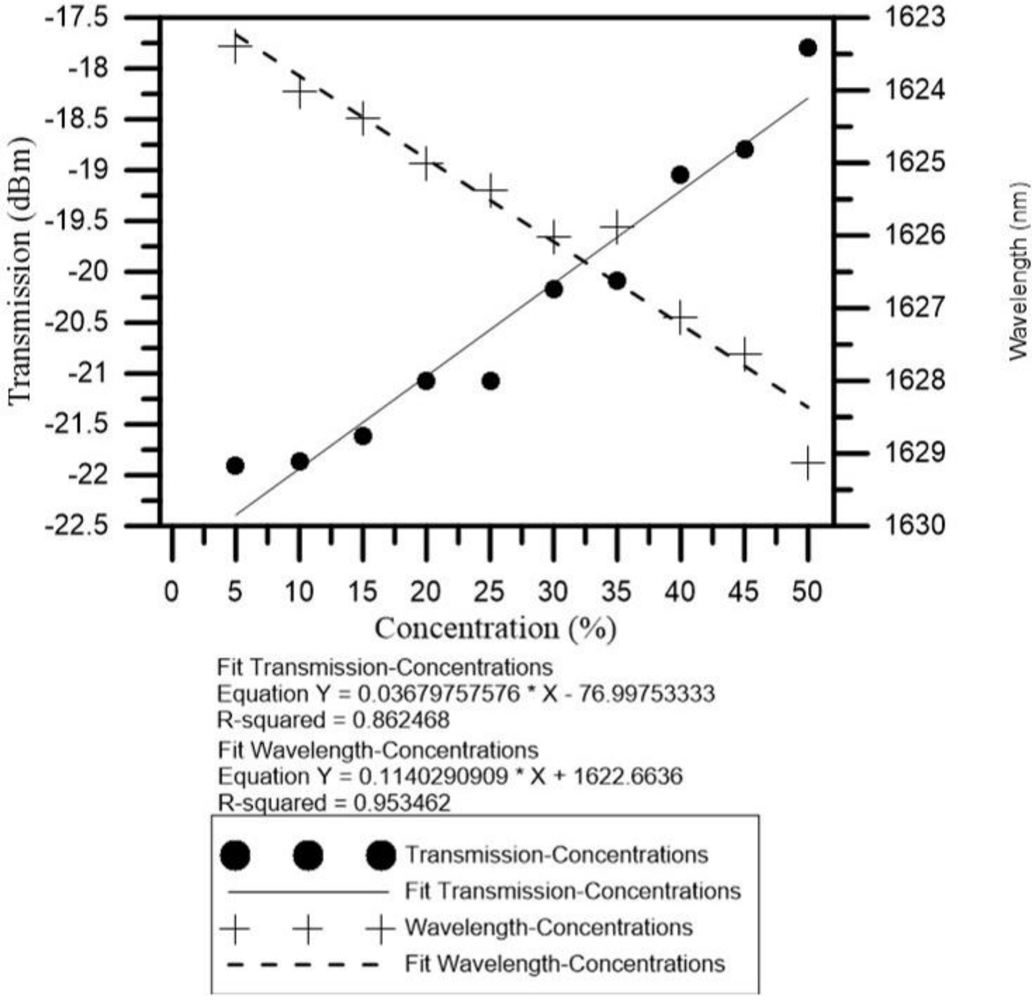


Figure 6. The linear graph of the sensor with Glucose

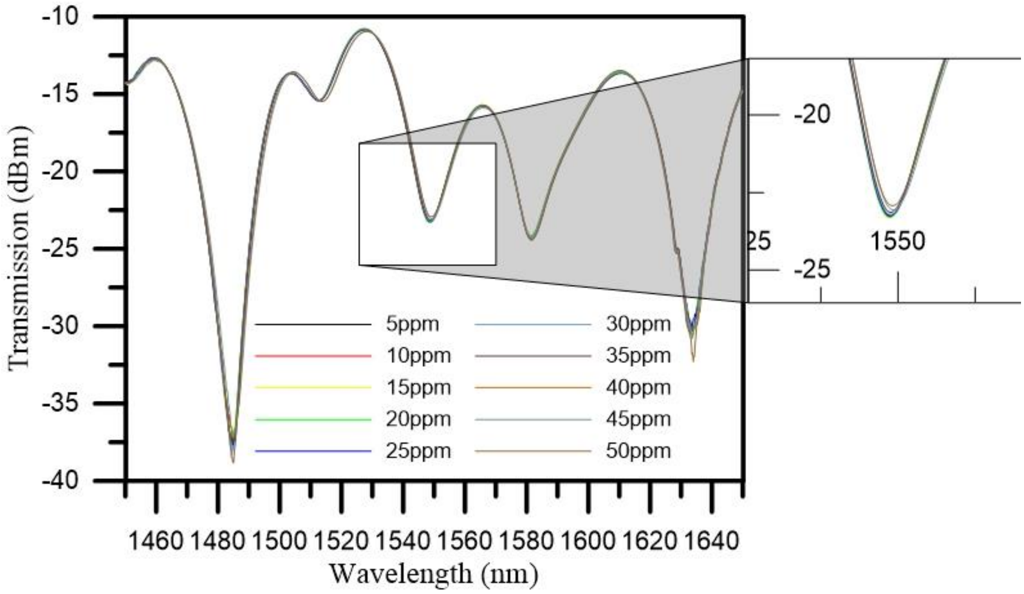


Figure 7. The signal of U-Shaped sensor with $HgCl_2$

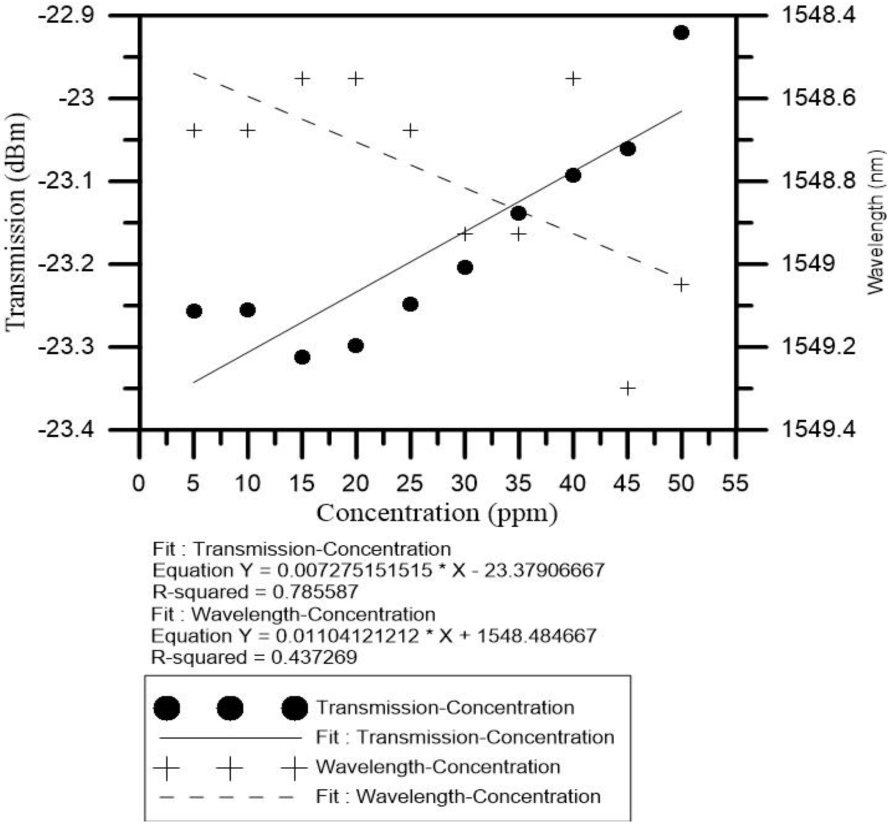
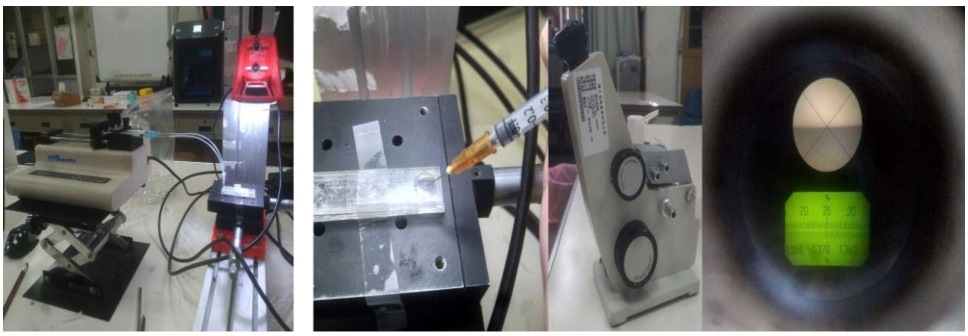


Figure 8.The linear graph of the sensor with $HgCl_2$

Results of Fabrication Microfluidics System

Figure 9(a) illustrates how we carry out an experiment to examine the quality of mixing from the microfluidics channels. In this research, a KDS100 syringe pump was used to control the volume and rate of two 1ml syringes. The 1mm-diameter pipe is used to connect the syringes with the microfluidics channel. After that, we will use two liquids with the same volume including DI water (0%) and Glucose (50%) in order to mix with each other. Figure 9(b) demonstrates the result of the mixing process. After getting the mixing liquid from the center of the outlet, with the rate from 0.01 ml/m to 0.05 ml/m, the findings from the Abbe refractometer show that the final liquid was mixed well with the mixing concentration is 25%.



(a) (b)

Figure 9. (a) The set up of experiment (b) Testing result

Conclusions and Recommendations

In this study, we do not only successfully justify the sensitivity of U-shaped Optical Fiber sensor to the different concentrations of Glucose and $HgCl_2$ but also fabricate completely the Microfluidics system. In the future, we will use the Microfluidics system to mix different types of liquid and detect the phenomena by the U-shaped Optical Fiber Sensor.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Basic Sciences, Engineering and Technology (www.icbaset.net) held in Marmaris/Turkey on April 27-30, 2023.

* We are highly thankful for the support of the organizers, editors, and reviewers who give suggestions and comments to inhance our research.

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To cite this article:

Tran, N.M., Hsu, H. C., & Chiang, C. C. (2023). A study of U – shaped optical fiber sensor for sensing different concentrations of glucose and ion liquid (HgCl2) and a fabrication of microfluidics systems. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 22*, 127-134.