Plastic Optical Fiber Sensing of Alcohol Concentration in Alcohol-Water Mixtures

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Abstract - *This paper presents the design and implementation of a new type of plastic optical fiber (POF) sensor to detect alcohol concentration in alcohol-water mixtures. Snell's law and total internal reflection phenomenon are explained to illustrate the main idea of this sensor in which detecting the light intensity to verify the standard of alcohol concentration. In this paper, Ze-max optic studio software has been used to reach the goals of this design.*

Key Words: Plastic Optical Fiber Sensor, Alcohol Concentration, Snell's Law, Total Internal Reflection, Ze-max Optic Studio.

1.INTRODUCTION

Development of a selective, sensitive, quick, and reliable measurement of alcohol is an essential task in several sectors including a wide range of industries, such as pulp or food industries, clinical, and forensic assays, and also agricultural and environmental analysis. However, ensuring the safety and quality of food and medical products can be a complicated task. This resulted that developing new-generation sensors with more modifications that guarantee the simplicity, reliability, and quick decision at a reasonable price is strongly required [1, 2]. This field has attracted many researchers in the world who have made a lot of efforts to propose several strategies for different application to measure the alcohol concentration [3–6].

From this point of view, a proposed of an optical measurement system of alcohol concentration using a plastic optical fiber (POF) is carried out. Starting from the principle idea behind this approach ending with the design and the proved results.

2. METHODOLOGY

In this research paper, Ze-max optic studio software has have been used to design the sensor and examine the results. Optics Studio is an advance level optical system designing software, engineered by Ze-max. Its unique features and functions make it one of the best optics studios around the world. Ze-max optics studio is an ideal software for creating models and designing optical systems. Designing of any optical system or illumination system is possible through Optic Studio including, projection, free from lenses, coherent lasers, LEDs, backlight, display, fiber optics systems and much more.

3. PRINCIPLE IDEA OF THE PROPOSED SENSOR

As the main purpose of this research is to use plastic optical fiber sensor to measure the concentration of alcohol, this is mainly based on the optical fiber total internal reflection. This phenomenon can be defined as light travels from the denser medium into another medium which is optically thinner; in this case, if the incident angle is equal to or bigger than the critical angle, this is what called the total internal reflection.

The term of the critical angle can be defined as the first angle for which the incident ray does not leave the first medium, namely when the angle of refraction is equal to 90°. Any incident angle exceeds the critical angle will consequently be reflected which means that it undergoes total internal reflection (TIR). Fig -1 shows the critical angle and the total internal reflection using two different materials which are water and air.

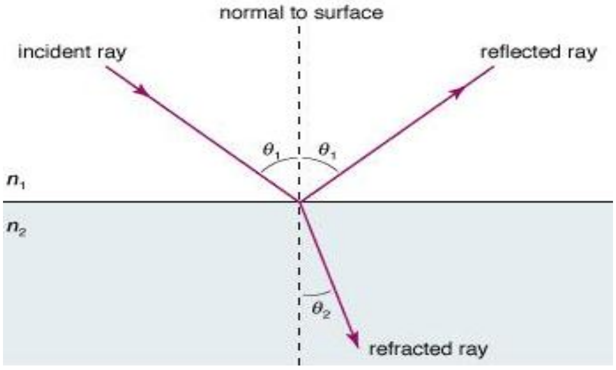


Fig -1: Explanation of Snell's law

Snell's law or the law of refraction should be understood to start working on this work. Therefore, this is an explanation of the Snell's law.

Formula for Snell's law:
$n_1 \sin\theta_1 = n_2 \sin\theta_2$
n_1= index of refraction of first medium.
θ_1= angle of incident.

n_2= index of refraction of second medium.
θ_2= angle of refraction.

The refractive index (n) of a material is the ratio of the speed of light (c) in a vacuum to the velocity of light in the material (cs). When $n_2 < n_1$, $\theta_1 < \theta_2$. As θ_1 increases, θ_2 will eventually reaches 90. This θ_1 which can be called θ_c is critical angle which can be obtained as follows:

$$\mathrm{n}_1 \sin\theta_1 = \mathrm{n}_2 \sin\theta_2.$$
$$\mathrm{n}_c \sin\theta_c = \mathrm{n}_2 \sin 90.$$
$$\mathrm{n}_c \sin\theta_1 = \mathrm{n}_2.$$
$$\sin\theta_c = {}^{\mathrm{n}_2}/_{\mathrm{n}_1}.$$
$$\theta_c = \sin^{-1}({}^{\mathrm{n}_2}/_{\mathrm{n}_1}).$$

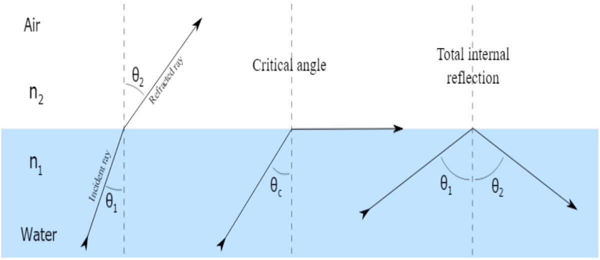


Fig -2: The critical angle and the total internal reflection

Total internal reflection is a powerful tool since it can be used to confine light. One of the most common applications of total internal reflection is in fiber optics, in which usually made of glass or plastic, for transmitting light. The construction of a single optical fiber is shown below in Fig -3.

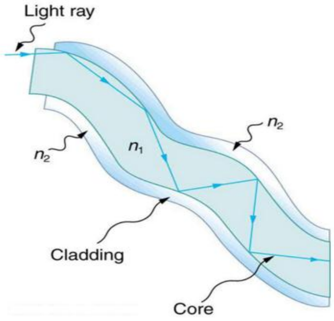


Fig -3: Total internal reflection in the core of optical fiber

The basic functional structure of an optical fiber consists of an outer protective cladding and an inner core through which light pulses travel. The difference in refractive index of the cladding and the core allows total internal reflection in the same way as happens at an air-water surface show in Fig -2. If light is incident on a cable end with an angle of incidence greater than the critical angle, then the light will remain trapped inside the glass strand. In this way, light travels very quickly down the length of the cable over a very long distance [7].

Importantly, It should be taken into consideration that the light propagate from a medium into another medium, some light continues to complete the total internal reflection but some light cannot complete the total internal reflection, this light transmits out which is the main cause of the power losses which is scoped in this work.

When mentioning the optical fibers, it is usually common to refer to those made of glass-based materials (glass optical fibers, GOF) for both the cladding and the core, irrespective of the proposed use. Nevertheless, plastic-based materials are also used for the core and cladding of optical fibers, in so-called plastic or polymer optical fibers (POF). The key advantages of this optical fiber that made the author to select this type in terms of the ease of installation and the performance are [8]:

Ease of Installation:

- No expensive termination tooling required.
- Simple end preparation (5-10 second dry polish).
- Smaller installed bend radius allowed than silica fiber (non-brittle).
- Large core diameters are NOT important for POF in Gb/s applications.

Performance:

- High bandwidth over broad wavelength range (lower material dispersion than silica).
- Simple methods for increasing BW using restricted launch (10 Gb/s x 100m).
- Lower modal noise than multimode silica fibers.
- Radiation hardness better than silica multimode fiber.

4. SENSOR DESIGN, RESULTS, AND DISSCUSTION

4.1SENSOR DESIGN

The prototype of the proposed sensor is shown in Fig- 4. The main idea behind this approach is to cut out part of the cladding of the POF, this ensures that the core of the POF is covered by the liquid that the alcohol concentration in it is measured.

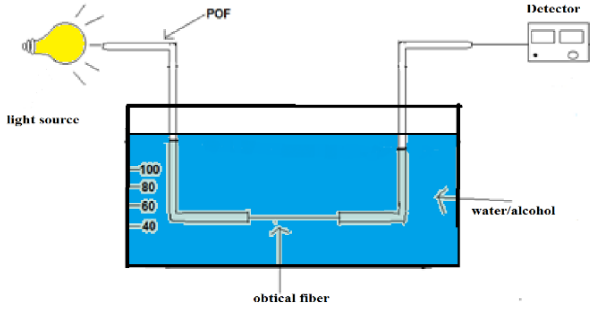
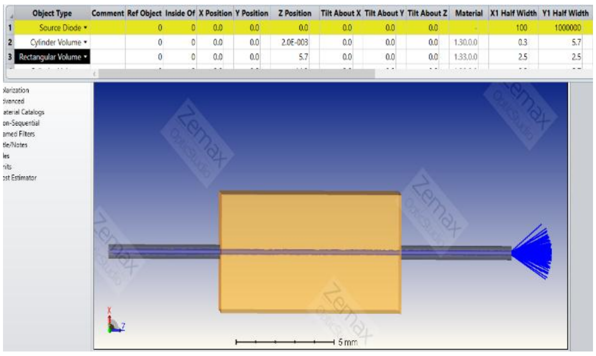


Fig -4: Schematic diagram of the experimental setup

Using ZEMAX as a software to represent the model is one of the key features of this work. in general, in ZE MAX, this model as shown in Fig- 5 constituted from six main components which are:

- Source diode.
- Cylinder volume 1 (the cladding of the fiber).
- Rectangular volume (the liquid).
- Cylinder volume 2 (the cladding of the fiber).
- Cylinder volume 3 (the core of the fiber).
- Detector surface.



	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position	Z Position	Tilt About X	Tilt About Y	Tilt About Z	Material	X1 Half Width	Y1 Half Width
1	Source Diode ▾		0	0	0.0	0.0	0.0	0.0	0.0	0.0	-	100	1000000
2	Cylinder Volume ▾		0	0	0.0	0.0	2.0E-003	0.0	0.0	0.0	1.30,0.0	0.3	5.7
3	Rectangular Volume ▾		0	0	0.0	0.0	5.7	0.0	0.0	0.0	1.33,0.0	2.5	2.5

Fig -5: The proposed system design

The diode shown in Fig- 6 used as a light source; it should be adjusted in order to produce light which enables the system to provide accurate results. The main characteristics that has been set in this source are: 1000000 analysis rays, 100 light rays, the wavelength is 0.55μm, and it produce 1 Watt. Analysis rays more than 1000000 can be used but ray trace will take around 3 minutes to finish the action “clear and trace” which delays the response.

The cladding material of the optical is an important component of the optical fiber. The refractive index of the cladding must be lower than the core’s refractive index. This is significant in order the total internal reflection occurs, when light passing through the core meets the cladding at an appropriate angle, it is reflected totally back into the core. In this work, the core diameter is 0.15mm, the martial of cladding is poly (hexafluoropropylene oxide) PHFPO which its refraction index is 1.3. Furthermore, increasing the value of the refractive index of the cladding increases the critical angle within the core fiber.

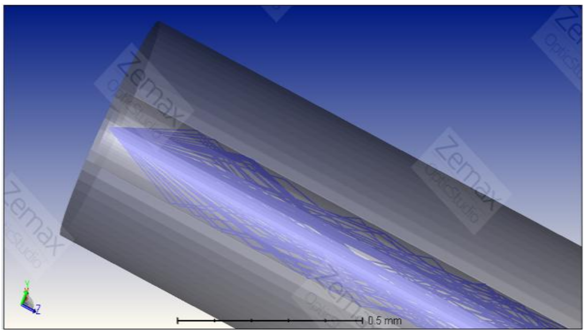
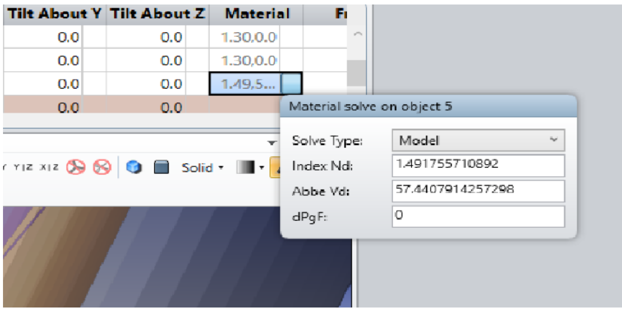


Fig -6: Light source rays

Fig- 5 highlights in orange the shape of the rectangular volume which is represent the liquid that its alcohol concentration is measured. The index refraction of the liquid is varieties based on these values: 1.3330, 1.3390, 1.3500, 1.3583, and 1.3660. These values represent different percentages of the alcohol concentration in the liquid.

As in Fig- 7, the core material is proposed to be Polymethyl methacrylate (PMMA) which its refraction index is 1.49175557 with diameter equals to 0.15mm. The core is always covered by cladding except during the rectangular where the liquid covers the core.



Tilt About Y	Tilt About Z	Material	Fi
0.0	0.0	1.30,0.0	
0.0	0.0	1.30,0.0	
0.0	0.0	1.49,5...	
0.0	0.0		

Material solve on object 5

Solve Type: Model
Index Nd: 1.491755710892
Abbe Vd: 57.4407914257298
dPgF: 0

Fig -7: The properties of the core setting

To measure the output power and to observe results from this system, an appropriate detector is located by the end of the core, this guarantees the detector to receive all the out light.

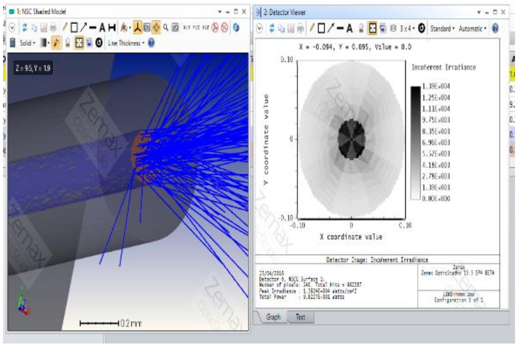


Fig -8: The detector of the proposed system

4.2RESULTS AND DISSCUSTION

1- When the refractive index of the liquid is equal to 1.3330 which means there is no alcohol in the liquid, the total power read by the detector is 9.8218E-001 watt.

In this case the refractive index of the core n_{cor} is 1.49175557 and the refractive index of the water n_{water} is 1.3330. The incident angle which is the critical angle can be easily calculated using Snell's law as follows:

$$\mathrm{n_{cor}}\ \sin\theta_1 = \mathrm{n_{water}} \sin\theta_2 .$$

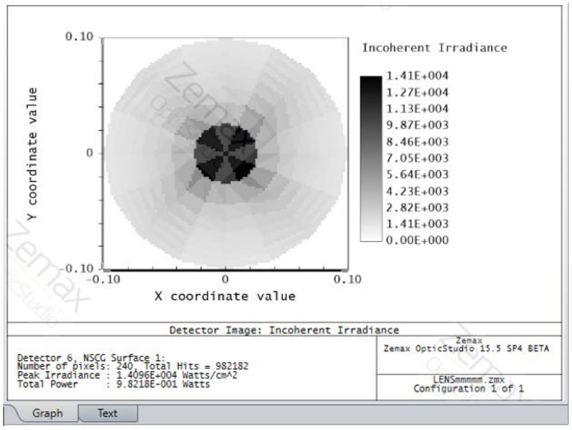
$$\mathrm{n_{cor}}\ \sin\theta_c = \mathrm{n_{water}} \sin 90 .$$

$$\mathrm{n_{cor}}\ \sin\theta_c = \mathrm{n_{water}} .$$

$$\sin\theta_c = {}^{\mathrm{n_{water}}}/_{\mathrm{n_{cor}}} .$$

$$\theta_c = \sin^{-1}({}^{\mathrm{n_{water}}}/_{\mathrm{n_{cor}}}).$$

$$\theta_c = \sin^{-1}\left({}^{1.3330}/_{1.49175557}\right) = 63.32636°.$$



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Detector 6, NSCG Surface 1:
Number of pixels: 240, Total Hits = 982182
Peak Irradiance : 1.4096E+004 Watts/cm^2
Total Power     : 9.8218E-001 Watts
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Zemax
Zemax OpticStudio 15.5 SP4 BETA
LENSmmmmm.zmx
Configuration 1 of 1
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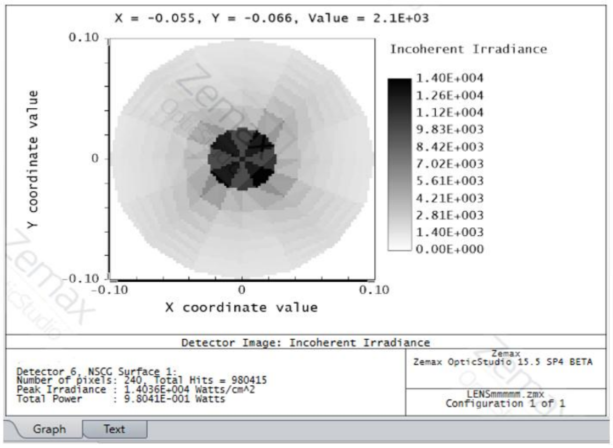
Fig -9: The result when the refractive index is 1.3330.

Power efficiency of this system can be defined as the ratio between the output power and the input power. The total input power is sat as 1 watt, and the output power which is the total power shown by the decoder which is 0.98218 watt. The efficiency power can be calculated as follows:

$$\text{Efficiency power} = \frac{\text{total power}}{\text{input power}}$$

$$\text{Efficiency power} = \frac{0.98218}{1} \times 100 = 98.218\% .$$

2- When the refractive index of the liquid is equal to 1.3390 which means 10% of alcohol the total power that has been read by the detector is 9.8041E-001 watt.



```
Detector 6, NSCG Surface 1:
Number of pixels: 240, Total Hits = 980415
Peak Irradiance : 1.4036E+004 Watts/cm^2
Total Power     : 9.8041E-001 Watts
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Zemax
Zemax OpticStudio 15.5 SP4 BETA
LENSmmmmm.zmx
Configuration 1 of 1
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Fig -10: The result when the refractive index is 1.3390

In this case, the refractive index of the core n_{cor} is 1.49175557 and the refractive index of the 10% of alcohol $n_{10\%}$ is 1.3390. The critical angle can be calculated using Snell's law as follows:

$$\theta_c = \sin^{-1}\left({}^{1.3390}/_{1.49175557}\right) = 63.8443°$$

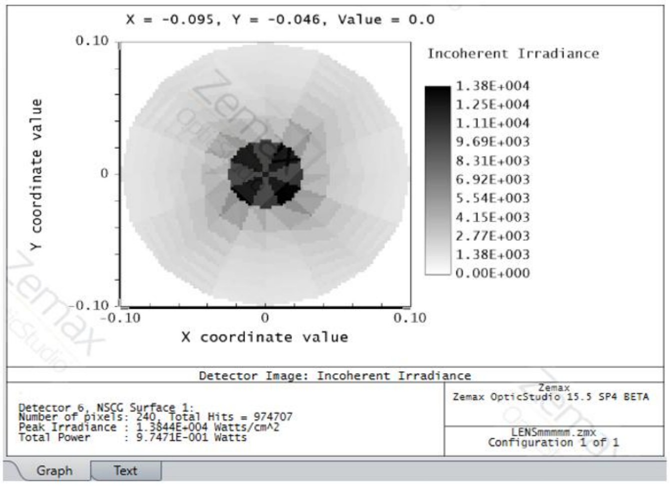
$$\text{Efficiency power} = \frac{0.98041}{1} \times 100 = 98.041\% .$$

3- When the refractive index of the liquid is equal to 1.3500 which means 30% of alcohol the total power that has been read by the detector is 9.7471E-001 watt.

In this case, the refractive index of the core n_{cor} is 1.49175557 and the refractive index of the 30% of alcohol $n_{30\%}$ is 1.3500. The critical angle can be calculated using Snell's law as follows:

$$\theta_c = \sin^{-1}({}^{1.3500}/_{1.49175557}) = 64.8197° .$$

$$\text{Efficiency power} = \frac{0.97471}{1} \times 100 = 97.471\% .$$



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Detector 6, NSCG Surface 1:
Number of pixels: 240, Total Hits = 974707
Peak Irradiance : 1.3844E+004 Watts/cm^2
Total Power     : 9.7471E-001 Watts
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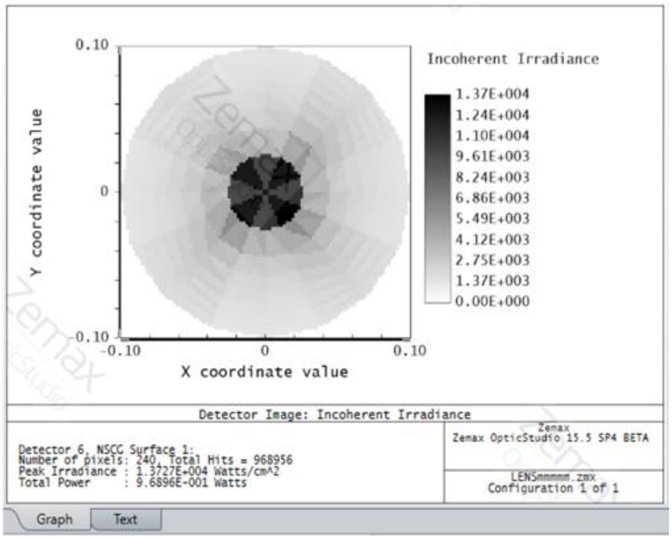
Fig -11: The result when the refractive index is 1.3500

4- When the refractive index of the liquid is equal to 1.3583 which means 50% of alcohol the total power that has been read by the detector is 9.6896E-001 watt. In this case the refractive index of the core n_{cor} is 1.49175557 and the refractive index of the 50% of alcohol $n_{50\%}$ is 1.3583. The critical angle can be calculated using Snell's law as follows:

$$\theta_c = \sin^{-1}({}^{1.3583}/_{1.49175557}) = 65.57979° .$$

$$\text{Efficiency power} = \frac{0.96896}{1} \times 100 = 96.896\% .$$



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Detector 6, NSCG Surface 1:
Number of pixels: 240, Total Hits = 968956
Peak Irradiance : 1.3727E+004 Watts/cm^2
Total Power     : 9.6896E-001 Watts
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Fig -12: The result when the refractive index is 1.3583

5- When the refractive index of the liquid is equal to 1.3583 which means 100% of alcohol the total power that has been read by the detector is 9.6161E-001 watt. In this case the refractive index of the core n_{cor} is 1.49175557 and the refractive index of the 100% of alcohol $n_{100\%}$ is 1.3660. The critical angle can be calculated using Snell's law as follows:

$$\theta_c = \sin^{-1}({}^{1.3660}/_{1.49175557}) = 66.305°.$$

$$\text{Efficiency power} = \frac{0.96161}{1} \times 100 = 96.161\% .$$

By analyzing the results obtained via this sensor, many features can be concluded. Noticeably, as a consequence of increasing the refractive index of the liquid, the output total power declined. Importantly, the refractive index changes being beyond this phenomenon because some light cannot complete the total internal reflection which means this light refracts or transmits out. Consequently, power is lost. Chart -1 demonstrates the relation between the refractive index and the out power.

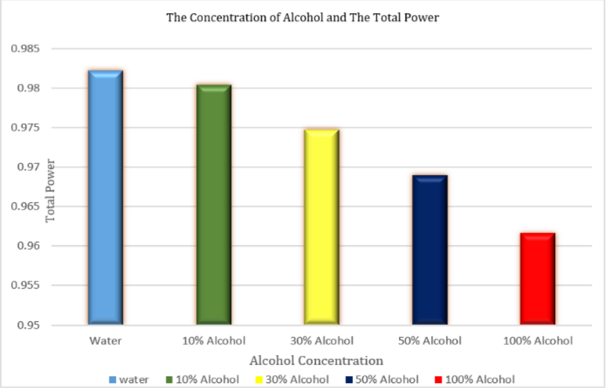

Chart -1 The association between the obtained results

Table -1 provides the associations between the alcohol concentration and its refractive index, the total output power, and the critical angle.

Table -1 The association between the obtained results

Material	Ref index	Total power	Critical angle
Water	1.3330	0.98218	63.32636°
10% Alcohol	1.3390	0.98041	63.8443°
30% Alcohol	1.3500	0.97471	64.8197°
50% Alcohol	1.3583	0.96896	65.57979°
100% Alcohol	1.3660	0.96161	66.305°

Quite understandably, any change in the concentration of alcohol means the change in refractive index leads to change the critical angle because as it is function in the refractive index as Snell's law illustrates. Therefore, as it is demonstrated by this work each change in the concentration has given a different critical angle.

5. CONCLUSIONS

This paper proposes a simple and accurate POF- type sensor for measuring alcohol concentration in alcohol-water mixtures. The main concept of this design is based on Snell's law and the total internal reflection phenomenon. The refractive index changes because of the changing in the alcohol concentration, this causes variation in critical angle and light intensity which results in a changing in the output power measured by the detector. Ze-max optic studio software has been used to design and implement the proposed sensor.

REFERENCES

[1] J. Sultana, M.S. Islam, K. Ahmed, A. Dinovitser, B.W.H. Ng, D. Abbott, Terahertz detection of alcohol using a photonic crystal fiber sensor. Appl. Opt. 57(10), 2426–2433 (2018). https ://doi.org/10.1364/AO.57.002426

[2] R. Boroujerdi, A. Abdelkader, and R. Paul, State of the Art in Alcohol Sensing with 2D Materials, vol. 12, no. 1. Springer Singapore, 2020.

[3] M. Shouran and I. Elhedmi, “Handheld Evidential Breath Analyser Design,” Int. J. Adv. Res. Electr. Electron. Instrum. Eng., vol. 9, no. 8, pp. 2247–2257, 2020.

[4] M. Morisawa and S. Muto, “Plastic optical fiber sensing of alcohol concentration in liquors,” J. Sensors, vol. 2012, no. 1, pp. 1–6, 2012.

[5] A. Weinert, Plastic Optical Fibers, Publics MCD, Munich, Germany, 1999.

[6] POF Consortium in Japan, Ed., Plastic Optical Fiber, Kyoritsu, Tokyo, Japan, 1997.

[7] A. Ghatak and K. Thyagarajan, Introduction to fiber optics. United States of America: Cambridge University Press, 1997.

[8] Kalymnios D. (1995) Plastic Optical Fibres (POF). In: Soares O.D.D. (eds) Trends in Optical Fibre Metrology and Standards. NATO ASI Series (Series E: Applied Sciences), vol 285. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-0035-9_37