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Investigation of U-shaped plastic optical fiber as refractive index sensor for liquids assessment

L.S.Supian*[a], Noor Hamisah Mohd Sahroni[b], Chew Sue Ping[a], Nani Fadzlina Naim[c], Harry Ramza[d]
[a]Department of Electrical and Electronics Engineering, Faculty of Engineering, National Defence University of Malaysia, 57000, Kuala Lumpur, Malaysia; [b]JKR Headquarters, Block G, Jalan Sultan Salahuddin, 50480, Kuala Lumpur; [c]School of Electrical Engineering, College of Engineering, UiTM, 40450, Shah Alam, Selangor; [d]Department of Electrical Engineering, Faculty of Industrial Technology and Informatics, Universitas Muhammadiyah Prof. Dr. HAMKA, Jakarta, 13420, Indonesia.

ABSTRACT

In this study, U-shaped fiber optic sensors are fabricated and analyzed to measure the sensitivity of the developed sensor and optimized the detection of the refractive index (RI) of a given liquid. Identifying the authenticity of the RI is very important in food processing, chemical, liquid security and pharmacy. In this research, three types of sensors with different curvature radii (3 mm, 4 mm, and 5 mm) and different angles (30°C and 60°C) with 60 cm length of polymer fibers have been developed to characterize and analyze which type of sensor that will give optimal reading. This sensor is expected to be used for future studies such as in bioengineering, food and liquid security and chemical detection. Each sensor is tested with several types of liquids that have different densities. The development of this RI sensor is also intended to detect a suitable temperature for RI of a liquid that is between 20°C - 55°C. The research analyzed the RI sensitivity using impurity-free liquid (mineral water) and non-impurity liquid (saline water and used cooking oil). The result is measured and collected using Optical Power Meter and a 6500-input light source. The selection of this U-shaped sensor is due to the robustness of this sensor in various environments, high sensitivity, and its simple construction. This work aims to produce a low-cost and highly optimal U-shaped sensor for detecting and measuring the RI of a liquid impurity and security in any environment.

Keywords: u-shaped, refractive index, pof, liquid security, optical sensor.

1. INTRODUCTION

Fiber optics technology is an advanced technology that can carry signals much farther and faster, and it has been used in multiple applications such as in the medical field, and environmental monitoring areas and one of the most important things in today's world is food safety [1]. The refractive index sensor is mostly applied to identify a particular substance, measure its concentration, and verify the purity of a medium [2]. This is due to its thin, flexible nature, ability to withstand high temperatures, and can be used in liquid environments [3]-[5].

Refractive index (RI) is the speed of light that passes through a medium where light is scattered through a medium. It is also known as the amount of bending of a light beam when it travels from one medium to another. The refractive index of any medium varies from one medium to another [6]. Table 1 shows the different RI indexes for different types of liquids [7]. The refractive index of a liquid contains crucial information about its physical characteristics, such as concentration and density, allowing the solution's composition to be determined and monitored such as the concentration of the medication in pharmaceutical manufacturing [8] and contamination in water [9]. There are a few types of geometries modified for plastic optical fiber for sensing purpose, for instance, a D-type, U-type shaped, uncladded, reflectance-based and others [3],[2],[10],[11]. Among these approaches, the U-shaped method has been examined and studied by many researchers because of its benefits such as ease of fabrication, simple experiment setup, and it suited for any point sensing due to its sensitivity, particularly for detecting a liquid's concentration and fat [12]-[14].

*sarah@upnm.edu.my; phone (+60)12926693;

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Table 1. Different RI indexes for different types of liquids

LIQUID	REFRACTIVE INDEX
Air	1.00
Water	1.33
Acetone	1.35
Ethanol	1.36
Acetic Acid	1.37
Olive Oil	1.46
Glycerin	1.47
Sunflower Oil	1.47
Argan Oil	1.48
Honey	1.49
Silicon oil	1.52
Sodium Chloride	1.54

The goal of this work presented here is to acquire the best measurement of a liquid's density by measuring the Refractive Index (RI) of any liquid medium. The sensor that will be produced is a double-sided U-shaped Plastic Optical Fiber sensor (POF). This sensor is chosen because of its robust nature, durability, and sensitivity [15]-[18]. Several parameters need to be considered in this experiment to produce the best and optimal sensor. The parameters are bending radii, angle, and length [10]-[13]. The major challenge to fabricate this POF sensor is physically changing the structure of the optical fiber so the light that propagates along the fiber can interrelate with any liquid solution that needs to be measured [19]. Other things that need to be considered are the heating temperature, bending force, and etching time [18]. The fabrication of U-shaped of Plastic Optical Fibers requires a heating process at the bending region to fabricate a permanent bent in the form of U-shape. Many researchers believe that keeping the optimal heating temperature and bending force is critical for achieving a consistent fiber core diameter [20]. However, no precise guidance on the appropriate heating temperature is provided.

For a better understanding and a deepened theory of the advantages of U-shaped POFs compared to straight-shaped POF sensors, it is important to study and consider the principle of evanescent waves in optical fibers. The principle of sensing operation is based on the overall internal reflection in the fiber which is attenuated through multiple internal reflections. If the fiber is in normal shape, no light will radiate out of the cladding. When the fiber is bent into a specific form, the light will radiate out. It is because of the critical bending radius that made the light mode radiates from the fiber by evanescent wave phenomena. The polishing depth is the key factor in fabricating this RI sensor. Less waveguide will guide the light because of the polished cladding. The deeper the polishing area, more light waves will radiate out [20]-[21]. Varied modes propagating over the fiber have different evanescent fields, which relate to the optical field diffused outside of the core. If the modes increase, the evanescent field will increase [22]. The effect of curvature radii and their angle were investigated to explore which sensor has the low-loss performance and give the best parameter of a suitable U-shaped RI sensor for the liquid environment [11]. The expected output of this sensor is to determine the sensor range sensitivity, the suitable polished angle, the propagation loss and cut of sensitivity, the optimum curvature radii, the optimum length, and the ideal temperature [23]-[25].

2. METHODOLOGY

The experiment in this work is divided into two parts which are the fabrication of the U–shaped POF sensor and the testing of the sensor with different liquids or solutions. For laboratory set-up, the sensor is dipped in a liquid solution. The RI can be identified by determining the light that transmits in the probe. The curvature radii, angle, and depth polishing all have an impact on the RI sensing performance. Different RI liquids were used in this experiment to analyze the optimum design of the RI sensor.

A U–shaped double sided polished is be fabricated and tested in this experiment. The basic numerical characteristics of U-shaped optical fiber were investigated and characterized such as its length (ι), curve radius (r), and thickness (t) of the sensor. This sensor then was tested on any liquid solution to sense its performance and to study which sensor will give an optimum result. The bending radius (r), deviation angle (θ), and polished depth (d) were enhanced to provide better sensitivity. The symmetrical double-side polishing allows excess contacts of POF cores with a liquid solution, which is favorable for better resolution. The sensing performance of each sensor produced will determine the absorption and refraction loss of each liquid tested. This research aims to propose an optimum RI sensor that can be used to assess the RI absorption of any liquids.

Figure 1 shows the double-sided U-shaped POF probe structure. The fiber is bent into a U-shaped with a radius of curvature, r. The angle, α, determines the polishing or grinding area. In this experiment, the study will be conducted with three different angles which are 30° and 60°. D is the polished depth parameter that affects the area of the evanescent wave to the liquid sample medium. The RI environmental medium is represented by n. The green line or n_{core} is represented as the core of the fiber and the black line or $n_{cladding}$ is represented as the cladding of the fiber.

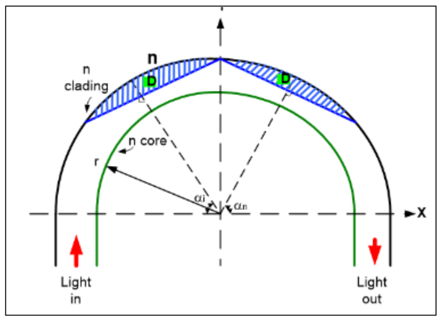


Figure 1. The schematic structure of the Double – Sided U – Shaped Plastic Optical Fiber.

Different methods such as heat process and mechanical polishing are implemented to form the symmetrical side-polished POF probe corresponding to multiple configurations of U-shaped plastic optical fiber-based on the bending radii and the angle is studied and compared. The method proposed is to find the optimum result having the highest sensitivity or low losses based on testing on each liquid.

2.1 Sensor Fabrication

The fiber is temporarily bent using a manual forced slowly to produce the shape of the curve as demanded. Heat is applied to the fiber until it managed to produce the right angle and radii that are required with an applied force. When the temperature is sufficient, the bend radius of the optical fiber reduces to the point that the loop became a U-shape that is fit for this experiment. When it is cool, the fiber is permanently bent into a U-shaped form.

POF sensor then was polished to create different angles of the unclad sections. The cladding at the middle portion of the fiber is then removed using a chemical etching and mechanical force. It was cleaned with a solution (alcohol and distilled water) after etching. The bare flat area on the core will be an oval-shaped surface that will have direct contact with any medium surrounding the fiber. Ethanol and grinding papers are used to taper the side of the POF probe.

2.2 Sensor Analysis

For this experiment, three types of liquids which are of pure water, saline and used oil with different RI is used to identify which types of the sensor is suitable for each type of liquid. An amount of 30 ml of liquid was used for this experiment. Figure 2 shows the experiment setup using an optical power meter and the light source.

The experiment began by taking a reference reading for each sensor without any liquid being tested. Comparing the test results with reference values are identified if the results fall outside the range of expected values. Then, each sample were tested to identify which sensor gives the optimal reading. The reading values that are recorded are decibels (dB), decibels milliwatts (dBm), and power (microwatt).

The sensor that was dipped into a different solution for at least 3 – 5 min is then washed with deionized water, for at least 2 minutes to remove all ions or residue at the tip of the sensor. The process is to ensure the accuracy of the laboratory results. On top of that, all the laboratory equipment must be washed with distilled water before use as well.

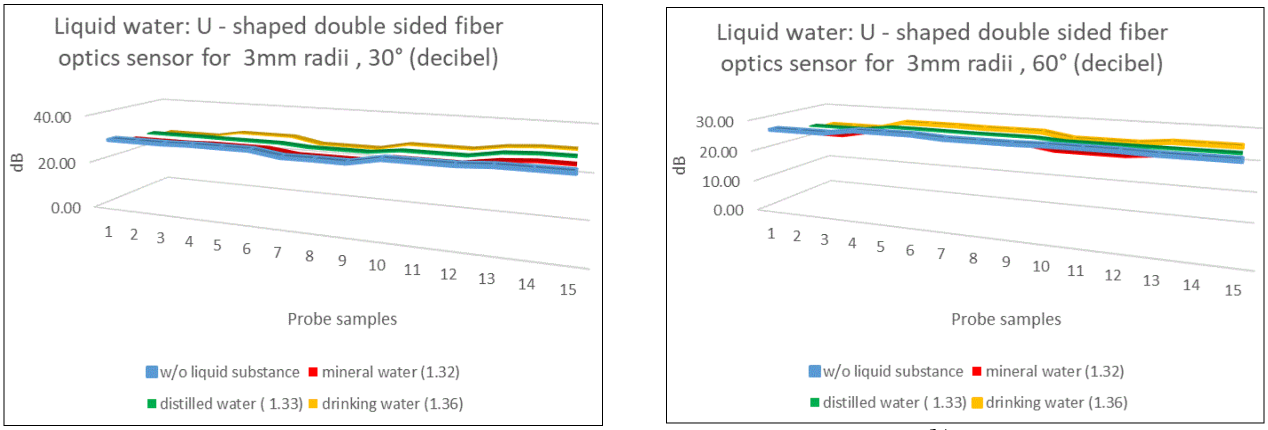
Figure 2. Experiment Setup

3. RESULTS AND ANALYSIS

Each sample is tested and the measurement is taken three times every 5 minutes until all the sample were tested. Each sample taken will begin with analysis without any liquid substance. This value will be the reference value. Next, these samples will be tested with pure water, saline water and used oil. The stable RI sensor can be identified from the data collection and analysis.

3.1 Pure Water

It is shown among the samples of polishing angles of 30º and 60º and radii of 3 mm, 4 mm, 5 mm, that sample 3 is the best sensor that can be selected for radii 3 mm with polishing angle 30° for pure water. This sample was chosen because it gave good results in terms of polishing depth and readings taken. Data can be very useful both in determining the population and in compiling the sample to be taken. The results also will be consistent and not altered by random events.



(a) (b)

Figure 3. (a) and (b). Comparison results for pure water (dB) designed for 3 mm radii with polishing angle 30° and 60°.

Figure 3 (a) and (b) illustrates the comparison result of the pure water test (decibel (dB)) for 3 mm radii with a polishing angle of 30° and 60°. As a result, it was found that these sensors did not show any major changes compared to the reference value even though it has the same radii. The different polishing angles of the sensor will not affect the measurement. From observation, the temperature of this liquid also plays an important role since this experiment is set up at a temperature between 20°C – 40°C, if these three liquids are placed in the same room, the temperature should be consistent or close to room temperature then no chemical reaction or foreign matter will occur because this liquid is impurity-free [26].

3.2 Saline Water

This experiment is continued to investigate non-impurity liquids such as saline water and used oils. Saline water is chosen because it has water parameters that contain a high concentration of dissolved salts that is used to study the sensitivity of the RI sensor. The selection of this normal saline water is intended to identify which sample probe sensor that will give the optimum reading since the impurity-free liquid does not show any differences compared to the reference value. RI sensor with the parameter of 5 mm radii and 30° polishing angle is suitable for saline water RI detection since it has sensitivity near to 1. This can be analyzed in Figure 4 shown where it depicts repeatability test for saline water and Figure 5 depicts sensitivity test for saline water where the value of R squared is 0.7062.

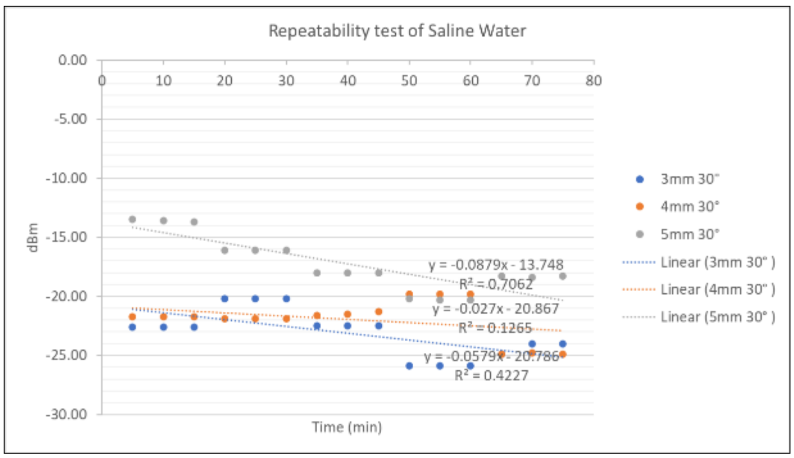


Figure 4. Repeatability Test of Saline Water

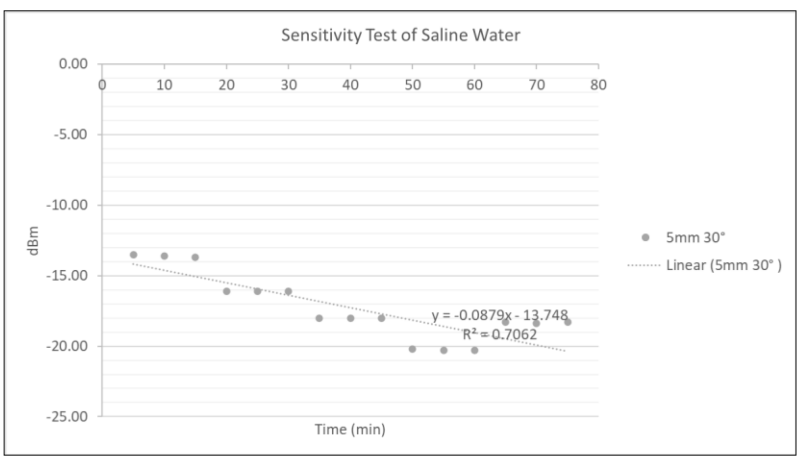


Figure 5. Sensitivity Test of Saline Water

3.3 Used Oil

In this experiment, used cooking oil (palm oil) was applied to analyze the stability and the sensitivity of the sensor produce. The refractive index of palm oil increased from 1.457 to 1.4653 after the oil was used in frying. A repeatability test and sensitivity test for the liquid sample also has been done to gain an accurate value of the parameter. As a result, the average R-squared value is 0.766, indicating that the sensitivity is very high. It is shown that a sample probe for 5 mm radii with a polishing angle of 60° is suitable for this liquid assessment. Figure 6 and Figure 7 show the repeatability test and sensitivity test for the used oil.

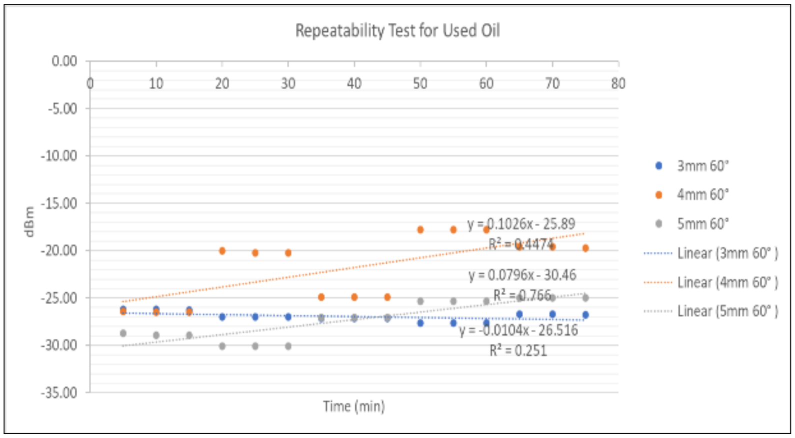


Figure 6. Repeatability Test for Used Oil

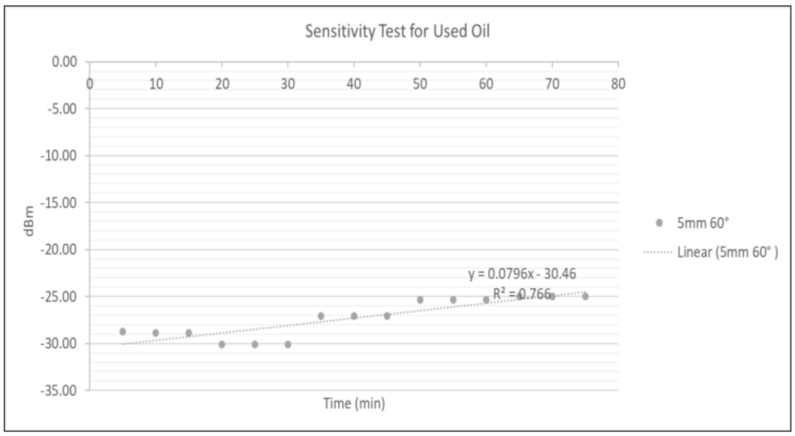


Figure 7. Sensitivity Test for Used Oil

4. CONCLUSIONS

This work is a research-based experiment on the development of the U-shaped double-sided polished plastic optical fiber or POF probe using plastic fiber to detect refractive index (RI) variance. By changing the POF structural modification techniques like tapering, side polishing, gap forming, and bending are employed to increase RI sensitivity. The goal of this project is to develop and investigates the RI sensor using a double-side polished U – shaped POF sensor that is varied on angle and radii having optimum sensitivity and efficiency. In this experiment, a U-shaped double side-polished fiber optics sensor is fabricated and experimentally demonstrated. The case study analyzes the RI sensitivity using impurity-free liquid (mineral water) and non-impurity liquid (saline water and used cooking oil). The result is measured and collected using Optical Power Meter and a 6500-input light source. The result shown in previous indicated that the bending radii of 5 mm with a polishing angle of 30° is suitable for saline water detection whilst sensor having bending radii of 5 mm with a polishing angle of 60° is suitable for used oil detection. Respectively it is suitable for RI range from 1.33 – to 1.55 within the temperature of 20°C to 40°C. In the future, several techniques can be investigated to improve the sensing performance such as the bending technique, the polishing depth performance, and the type of fiber.

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