Characterization of POF for liquid level and concentration sensing applications

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Abstract. Measuring liquid level and solution concentration play an important role in commercial and technological applications. For years, polymer optical fibers (POFs) have been very attractive for industrial applications because of their unique characteristics. In this work, we created simple, low cost and efficient set-up for sensing liquid level and solution concentration using POFs. We have calculated the acceptance angle of the POF to be 30° from numerical aperture (NA) measurements (NA≈0.500). Images of a single POF showed the presence of impurities within the fiber which can contribute to power loss of the transmitted light. Light leakage was also observed when the fiber was bent to a tight radius, i.e. beyond its minimum bend radius of 15 mm. The experimental results show that as liquid level increases, the output power decreases. Furthermore, when the liquid concentration was increased, its response showed a greater loss of optical power due to the light rays in the submerged region of the POF tend to be refracted out of the fiber instead of being totally internally reflected and transmitted when index of refraction of the surrounding liquid medium is increased.

1. Introduction

In the development of fiber optic technology, different researches had been conducted which are focused on suitable design of fibers. Some of the studies being done were directed to the designing of sensing systems with the use of these optical fibers, which led to the production of fiber-based sensing devices and components. At present, the development of sensors is remarkably responding to the needs and demands of consumers.

Nowadays, fiber optic technologies have been developed for application communication systems. However, the developments of high quality and competitively priced opto-electronic components and fibers have contributed to the growth of fiber optic technology in sensing applications [1,2]. In addition, low production cost and installation have contributed to the prevalent use of optical fibers in sensing. In recent years, optical fiber based sensors have attracted increasing interest owing to their inherent characteristics such as immunity to electrical noise, ease of miniaturization, the possibility of real time monitoring and remote sensing [3]. Additional advantages of fiber optic sensors in

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comparison with conventional sensors are immunity to electromagnetic interference, multiplexing capability, distributive sensing and non-intrusiveness, lightweight, high sensitivity and spark-free [4]. These features make them a powerful tool for environmental and industrial process monitoring.

Liquid-level measurements in practice have been attracted by the splendid properties of optical fiber sensors. Level detection plays an important role in commercial and technological applications [5] such as monitoring of the water level in catchment areas, scrutinizing of illegal dumping of trash and pollution in canals, early warning of impending drought [4], monitoring of liquid level in oil tanks which is important in the petroleum and chemical industries [6]. Chemical industries widely require fiber-based liquid sensors since they are non-electrical and spark-free, and would not likely cause severe disasters when controlling volatile liquids.

Correspondingly important is the measuring and controlling of the concentration of solutions in chemical industries, sugar-manufacturing and pharmaceutics, to guarantee and improve product quality [7]. The use of optical fibers in measuring solution concentration is a necessity to some industries since they are safe to be used in volatile liquids. Plastic optical fibers (POF) are also resistant to certain organic acids which allow them to be used to measure concentrations of some strong acids in water [8, 9].

In the present work, we characterized POFs made form Polymethyl Methacrylate (PMMA) core material and fluorinated polymer cladding material for liquid level sensing and concentration sensing applications. Single POF sensor system was constructed and utilized for the liquid-level sensing tests. Two single POFs were used to create the sensor arrangement—one was unstripped and the other fiber’s cladding was stripped—to examine how would the stripping of cladding affects the response of the fiber sensor to the increasing level of liquid. Two fiber bundles were also made for the sensing of variation in concentration of glycerin solution. The prepared POF was then subsequently subjected for numerical aperture measurement and structure examination.

2. Experimental procedures

2.1. Numerical aperture measurement

Numerical aperture (NA) of an optical fiber is the measure of its ability to gather light. NA was determined by allowing the laser beam pass into the fiber and measuring the angular dependence of the intensity of the transmitted light as shown in Figure 1. Measurement of the numerical aperture of POF was done four times using four varying lengths of single POF. The lengths of the fibers were 6 inches, 12 inches, 18 inches and 24 inches. The experiment was then carried out in a dark environment to assure that no stray lights aside from the source could contribute to the measurement to be obtained. Blue chromalase laser having 500mW power output operating at 488 nm served as the light source.

The laser beam was coupled into the single POF. The light which experiences total internal reflection was transmitted within the fiber until it reached the fiber end. This transmitted light was received by the sensor probe and the corresponding output power was then displayed in the screen of the Thorlabs Optical Power and Energy Meter detector. The far-end of the fiber was positioned at the center of the angular translator so that the distance between the far-end of the fiber to the sensor probe was equidistant at any angle. The single fiber was fastened to some wood blocks using an adhesive tape in order to ensure stability of the set-up. In this work, bending of the fibers along its length was avoided so that the light coming from the source travels in straight path and hence, maximum power was received by the detector and the intensity of transmitted light was measured at different angles. NA was calculated using this equation:

\[ NA = \frac{1}{2}(x_2 - x_1) \]  

where the two values of \(x\) corresponds to the 5% intensity points. Numerical aperture was then determined using one half of the full angle between the two 5% intensity points.
2.2. Assembly of the liquid-level sensor
The sensing capability of the liquid-level sensor was examined by immersing the POF in liquid and measuring the power transmitted through it as the liquid level was increased. The sensing performance of the concentration sensor system was evaluated through submerging it first, in distilled water, then in 20, 40, 60, 80, 100% v/V (v is the volume of glycerol and V is the total volume) concentration of glycerin solution. Glycerin is chosen in this study since it has important roles for various industrial applications. A design for liquid-level sensor is presented in this study as shown in Figure 2a. Figure 2b shows a simple sensor arrangement for liquid-level and concentration sensing and was constructed out of the characterized POF. This is based on the mechanism of total internal reflection in the optical fiber. The sensing performance of the fabricated fiber sensor system was installed and liquid level measurement was conducted at ambient room temperature.

A container was filled with distilled water up to 100mm level. The light intensity transmitted through the fiber was first recorded before it was immersed in the water. The measurement of the intensity of the transmitted light was then recorded in every 10 mm level of the sensor. The set up for the measurement of the index of refraction of the liquid medium and the geometry of the coupling between the emitter and receiver was also installed. The bundled POFs are arranged parallel to each other and their tips are placed in front of a reflector (mirror). The light is launched into the transmitting fiber bundle and on emergence is then reflected by the reflector and is received by the receiving fiber.
The light intensity is sensed by a power meter to be displayed as output power in micro watts. The incident light on the reflector forms a cone of emittance from transmitting fiber. It is reflected back in the form of expanding cone of light. The cone diameter depends on refractive index \( n \) of the medium (liquid) and the separation between the reflector and the probe at any fixed position between probe and the reflector. If the space between the probe and the reflector is filled with a liquid of refractive index \( 'n' \), then cone angle

\[
\theta_a = \sin^{-1}\left(\frac{NA}{n}\right)
\]  

(2.2)

here \( NA \) is the numerical aperture of the fiber and \( n \) is the index of refraction of the medium.

In evaluating the sensing performance of the concentration sensor, the sensor was first immersed in distilled water, then in different concentrations of glycerin solution, 20, 40, 60, 80 and 100% v/V, where \( 'v' \) is the volume of the soap and \( 'V' \) is the total volume of the solution. The power that was transmitted at the emitting fiber and received at the receiving fiber, then transmitted to the end of the receiving fiber was read by the power meter every time the solution concentration is varied. The separation distance between the tip of the probe and the reflector was varied to check how it will affect the light as read by the detector. The spacing between the tip of the probe and reflector is 10 mm and the readings were taken in successive steps of 5mm.

3. Results and discussions

3.1. Power output transmitted through POF

Figures 3a show the actual power of the transmitted light versus the sine of the angular position where the measurement was taken. The plot tells that the maximum power of light transmitted through the fiber was taken at the center orientation or where the fiber end and the sensor probe of the detector is in line with each other. It can be noticed that as the sensor probe was rotated in either clockwise or counterclockwise direction, the intensity of the transmitted light that was recorded decreases. Symmetry in the measurement was found with respect to the center.

![Figure 3a](image)

(a) Transmitted power through the fiber vs the sine of the angular position

![Figure 3b](image)

(b) Intensity of light (in normalized points) received by the detector as a function of the acceptance angle from the four single plastic optical fibers of different lengths.

It can be also observed that a decrease in the peak power taken at the center orientation as the length of the fiber is varied. It can be noticed that as the length of the fiber gets longer, the maximum...
power of light transmitted through the fiber taken where the fiber end and the sensor probe of the detector is in line with each other, decreases. Since attenuation is directly proportional to the distance travelled by light, the longer the fiber, the farther the light has to travel, and the more the optical signal is loss. As light travels in the core, it interacts with the molecules in the core. This is attributed to the elastic collisions between the light wave and the molecules which result in Rayleigh scattering. If the light is scattered at an angle that does not support continued forward travel, the light is diverted out of the core and attenuation occurs. Optical power loss could also be because there is a reflection of minimal amounts of light in all directions as the signal is being transmitted through the fiber, some of the light goes out of the core, while some travels back to the source. Beer’s Law, tells us that transmitted power decreases exponentially with propagation distance through the fiber. Hence, there is a greater decrease in the output power as the fiber’s length is increased. The numerical aperture of the fiber is shown in Table 1.

| Fiber Length | NA   |
|--------------|------|
| 6” fiber     | 0.561|
| 12” fiber    | 0.505|
| 18” fiber    | 0.583|
| 24” fiber    | 0.584|

3.2. Structure of the plastic optical fiber (POF)

Single POF was viewed at a closer look using a microscope. The image was then viewed in the computer through the Digital CCD Camera which is attached to the microscope. The structures of both bent and straight fibers were inspected. The fiber was first observed without bending while the light is passed through its length. Figure 4a shows the image, showing the presence of impurities and defects in the fiber. These impurities and defects cause light attenuation within the fiber. Attenuation occurs when there is absorption of the light that travels down the fiber which absorption is induced by the imperfections in the atomic structure of the optical fiber by the presence of oxygen defects or by the diffusion of hydrogen molecules into the fiber. Thus, in sensing, a decrease in output power can be accounted even without exposing the fiber to variations of the index of refraction of the surrounding medium. The output power read by the detector is lesser than that of the power emitted by the source as the light has been transmitted through the length of the fiber. Hence, it is necessary to measure the output power before the sensing tests be conducted so that the optical power loss that will be accounted during the sensing is just caused by the change of the refractive index of the medium where the fiber is being subjected.

Figure 4. (a) Shows presence of impurities and defects and (b) shows leakage of light in the bent region of the fiber.

The plastic fiber was bent and the bent area was investigated shown in Figure 4b. The defects are evident and are indicated by the presence of lines and dots. It can also be noticed that light rays tend to escape out of the fiber in the bent region. Thus we can say that there is loss of total
internal reflection of light in the bent region since the bend curvature creates a very sharp angle for the light to be reflected back into the core, and some of it escapes through the cladding layer, causing attenuation. This attenuation rapidly increases as the radius is decreased to an inch or less. It is very important that in creating the sensor configuration, the fiber must not be bent beyond its minimum bending radius, which is 15 mm, so as not to cause core breakage and to avoid a large amount of power loss.

3.3. Liquid level sensor performance

Table 2 shows no apparent loss of total internal reflection (TIR) when the fiber was bent and stripped. Hence, it is fine to utilize these fibers in sensing since the loss of TIR that will be accounted in the sensing will just be due to the change of the index of refraction of the surrounding medium and not to the sensor’s configuration. In this test, the sensor’s response depends on the index of the core, the cladding layer, and the liquid in test. Several trials were done in this experiment and all show the same response.

Table 2. Power transmitted through the fiber (unstripped: straight and bent; stripped: straight and bent).

| Fiber description           | Output Power (μW) |
|----------------------------|-------------------|
| Straight, unstripped fiber | 317.1             |
| Bent, unstripped fiber     | 316.9             |
| Straight, stripped fiber   | 316.6             |
| Bent stripped fiber        | 316.4             |

Figures 5 and 6 show the response of both the stripped and unstripped fiber sensors to increasing level of distilled water first, then to glycerin solution of different concentrations (20, 40, 60, 80, 100% v/V, where ‘v’ is the volume of the glycerin and ‘V’ is the total volume). All showed the same response, that is, the transmitted power accepted by the detector decreases as the level of liquid increases. The decrease in the transmitted power read by the detector at the output end of the fiber is caused by the loss of total internal reflection (TIR) as the liquid gradually covers the length of the fiber when its level was raised. When the fiber was immersed in the liquid and as the liquid level was increased by 10 mm increment, some of the light rays traveling through the fiber’s length in the submerged region of the fiber were refracted, instead of being totally internally reflected.

![Figure 5. The response of single POF (unstripped) to increasing level of water and glycerine solution concentrations.](image-url)
Figure 5 is the response of the unstripped fiber sensor to increasing level of liquid with different concentrations of glycerin solution. It can be deduced from the given plot above that as the concentration of the glycerine solution was increased, the transmitted power measured by the detector decreases as the liquid level increases. The decrease of the transmitted power per level per concentration is not proportionate. This might be because of the inhomogeneity of the solution. As presented in Table 3 is the unstripped fiber’s response to increasing level of liquid and increasing glycerine solution concentration in terms of the slope, $\Delta P/\Delta d$. The negative slope indicates that the output power measured by the detector at the fiber’s end decreases as the liquid level increases. It can be noticed that as the concentration of glycerine solution was increased, the slope becomes more negative which means that as the level of liquid was increased with increasing concentration. There is a greater power loss experienced in the region of the fiber that was immersed in the liquid. This is because light rays tend to leak out from the fiber as the refractive index of the surrounding medium is increased.

| Liquid in test | $\Delta P/\Delta d$ (μW/mm) |
|---------------|---------------------------|
| Distilled water | -0.465                    |
| 20% v/V       | -0.803                    |
| 40% v/V       | -0.886                    |
| 60% v/V       | -1.195                    |
| 80% v/V       | -1.310                    |
| 100% v/V      | -1.366                    |

Figure 5 is the response of the unstripped fiber sensor to increasing level of liquid with different concentrations of glycerin solution. It can be deduced from the given plot above that as the concentration of the glycerine solution was increased, the transmitted power measured by the detector decreases as the liquid level increases. The decrease of the transmitted power per level per concentration is not proportionate. This might be because of the inhomogeneity of the solution. As presented in Table 3 is the unstripped fiber’s response to increasing level of liquid and increasing glycerine solution concentration in terms of the slope, $\Delta P/\Delta d$. The negative slope indicates that the output power measured by the detector at the fiber’s end decreases as the liquid level increases. It can be noticed that as the concentration of glycerine solution was increased, the slope becomes more negative which means that as the level of liquid was increased with increasing concentration. There is a greater power loss experienced in the region of the fiber that was immersed in the liquid. This is because light rays tend to leak out from the fiber as the refractive index of the surrounding medium is increased.

Figure 6. The response of single POF (stripped) to increasing level of water and glycerine solution concentrations.

In Figure 6, the response of the stripped fiber sensor to increasing level of liquid with increasing concentration of glycerine solutions is shown. There is also a decrease of the output power as the level of liquid increases. Furthermore, there is a greater power loss and hence a greater decrease of output power accepted by the detector as the solution concentration was increased. However, we can observe that compared to the unstripped fiber, the stripped fiber sensor has a better sensing capability since its response to increasing liquid level and increasing solution concentration in terms of the slope, as shown in Table 4, it is more negative than that of the unstripped fiber’s response as shown in Table 3. This is because the bare fiber is more exposed to the change of the index of refraction of the
surrounding medium as its concentration varies. When the bare fiber is immersed in the liquid, light escapes out of the core in the submerged region since the liquid in test has a greater index of refraction than that of the fiber’s core. Total internal reflection will only occur if the light strikes a denser medium and is approaching a less dense medium. In the stripped fiber, the air served as its cladding and TIR occurs since the air has a lower index of refraction than that of the core, that is \( n_{\text{air}} = 1 < n_{\text{core}} = 1.42 \). But when the stripped fiber was immersed in the distilled water with \( n = 1.33 \), greater than that of \( n_{\text{air}} = 1 \) which served as the bare fiber’s cladding, some of the light rays traveling along the fibers are refracted and escape out of the fiber when they pass on the submerged region. As the water was then replaced with glycerine solution of 20, 40, 60, 80, 100% v/V, where ‘v’ is the volume of the glycerin and ‘V’ is the total volume, the medium in which the fiber was submerged becomes denser, and hence higher and higher index of refraction. Thus, greater is the accounted optical power loss for higher concentration of glycerol, that is, the response of the single, stripped fiber sensor in terms of the slope, \( \Delta P/\Delta d \), becomes more and more negative as the solution concentration increases.

| Liquid in test | \( \Delta P/\Delta d (\mu W/mm) \) |
|---------------|-------------------------------------|
| Distilled water | -0.881 |
| 20% v/V | -1.073 |
| 40% v/V | -1.181 |
| 60% v/V | -1.363 |
| 80% v/V | -1.440 |
| 100% v/V | -1.671 |

The response observed shows a linear response where the slope is negative; indicating that as there is an increase in the level of water, there is a corresponding decrease in the output power. The response of the fiber sensor is in accordance to the hypothesis. Theoretically and experimentally proven, the power received by the detector should decrease when liquid level rises, that is, if the index of refraction of the surrounding medium is greater than that of the cores.

3.4. POF as concentration sensor

A simple arrangement for sensing the change of solution concentration using the fiber bundles has been assembled. The ends of the fabricated fiber bundles were polished with a suitable grit (600-grit) to flatten and achieve uniform fiber bundle tips. We preferred to use fiber bundles so as to achieve an easy and better coupling of light into the fiber. One fiber bundle served as the light emitter, and the other as light receiver. As light from the source was emitted at the end of the emitter fiber, the power received by the receiving fiber, and the by the detector at its end is dependent on the refractive index ‘n’ of the liquid. Thus, when concentration of the glycerol was varied, and since concentration and index of refraction are directly related, the transmitted power read by the detector also changes. Several trials were done in this experiment and all show the same responses.

When the probe was at close proximity of the reflector, a minimum output power is observed. The increase in separation distance between the probe and the reflector increases the light launched into the receiving fiber which results in rapid increase of output current and reaches to a maximum with steep front slope as presented in Figure 7. It can be deduced that at any separation the light reaching the receiving fiber is dependent on the concentration of solution. After reaching maximum, the light intensity starts decreasing for larger separation resulting in moderate back slope. The increase in the area of transmitting fiber cone with increasing separation and inverse square law caused the decrease in output power. The inverse square law states that the intensity of illumination is proportional to the inverse square of the distance from the light source. So, entire region of the receiving fiber tip is covered by the reflected beam at higher values of the displacement, and there is no change in the overlap area, then the fall in output power follows the inverse square law. Emitting fiber gets narrower, and hence the decrease in output power. But the response is opposite. This reverse response of the
fiber bundle might be because of the arrangement of the fibers bundled together. It is possible that the light as it travels within the fiber bundle with the presence of the liquid surrounding it might just travel from one fiber to another fiber. As $n$ of the solution increases with concentration, it might be that the light rays being refracted by one fiber is absorbed by the other fiber, and hence the increase in output power.

![Figure 7. The output power vs. the displacement (distance between probe and reflector).](image)

4. Conclusions

In this work, we have characterized plastic optical fibers of different lengths. We have successfully design sensor arrangements in liquid level and concentration sensing purposes and the performance were evaluated using distilled water and glycerin solutions of varying concentration (20, 40, 60, 80, 100% v/V). The calculated numerical aperture of the fiber is 0.5 and the fiber’s acceptance angle is measured 30° allowing light to be transmitted through its length at light’s entrance angle equal or less than 30° measure from the fiber axis of propagation. The micrograph images have revealed the presence of defects and impurities in the fiber. It was also found that the stripped fiber sensor has a better sensing capability than that of the unstripped fiber since it has higher response to increasing liquid level and increasing solution concentration. These results can be accounted because the bare fiber is more exposed to the change of the index of refraction of the surrounding medium as its concentration was varied. When the glycerol concentration was increased, it was found that the transmitted output power also increases as shown in the increment of peak power. Results revealed that an increase in index of refraction gave a corresponding increase of the transmitted output power.

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