Real-time Liquid Level Measurement using a Plastic Optical Fiber (POF)

Bakti Dwi Waluyo[1], Joni Safrin Rambey[2], Ressy Dwitias Sari[3]

{ bakti_dw@unimed.ac.id[1], joni@unimed.ac.id[2], ressy@unimed.ac.id[3]}

Department of Electrical Engineering Education, Universitas Negeri Medan, Medan, Indonesia[1,2]
Department of Information Technology and Computer Education, Univeritas Negeri Medan, Medan, Indonesia[3]

Abstract. This research presents a low-cost sensor for measuring liquid levels using plastic optical fibers (POF). The sensor reduces the scattering-based optical losses in the fiber, which increase linearly with the liquid height. A U-bent fiber probe and photodetector are used to detect the change in optical intensity. The U-bent probe serves as a test probe for measuring the liquid level. The voltage response difference of the photodetector provides liquid level measurement. This study demonstrates the sensor's responsiveness to liquid level fluctuations above 55 cm at varying temperatures. Sensitivity levels of 1.4 and 3.3 mV/mm were achieved for water level fluctuations below and above 45 cm, respectively. Furthermore, the sensor demonstrated consistently stable responsiveness over multiple cycles.

Keywords: Real-time liquid level measurement, Plastic optical fiber sensor, U-bent fiber optic probe.

1 Introduction

Real-time monitoring of water levels is crucial for several industrial processes, including the chemical industry, which necessitates substantial storage capacity for water, oil, and chemicals [1]. Most liquid level sensors currently available in the market are mechanical or conventional [2], ultrasonic [3], or electrical based [4], but their size limitations, noise susceptibility, and inability to function with conductive liquids that can incite explosions present some limitations. Therefore, optical sensors are considered a superior alternative. Optical sensors enhance safety measures, reduce maintenance expenses, minimize mechanical components, and allow for continuous level measurements. The advancement in optical-based liquid-level sensors research leads to a refined performance, making them a better fit for liquid-level monitoring in the chemical sector.

Over the past thirty years, various compact and dependable fiber optic sensor schemes have been developed. Most of these sensors rely on changes in liquid level caused by alterations in the refractive index surrounding the sensing element. Examples of fiber optic sensor

ICIESC 2023, October 24, Medan, Indonesia

DOI 10.4108/eai.24-10-2023.2342136

configurations grounded on either wavelength or phase propagation of light encompass fiber Bragg grating [5], multimode fiber [6], and long-period grating [7]. D-shaped fiber [8], modal interference using few-mode fiber [7], and polarization-maintaining fiber [9] are sensors that can only detect liquid levels up to 20 cm, according to the literature. Although these sensors are highly sensitive, they have limitations, such as requiring precise optical connectors and expensive photodetection systems. Evanescent wave (EW) fiber optic sensors offer a cost-effective option for intensity-modulated level sensing. However, certain EW configurations incorporate delicate silica optical fibers, limiting their use to smaller measurement ranges.

POF or plastic optical fiber sensors have become a viable alternative to silica fiber due to their lower cost, ease of installation and coupling, and durability [10]. Bent and side polished POFs have been proposed as discrete sensing elements or helically mounted on a solid support [11]. Other reports have demonstrated the optical coupling between a pair of twisted POFs, which depends on the liquid medium [12]. Additionally, buffering fiber with micro-holes [13] or V-grooves [14] has been utilized to measure levels. Most of the sensing schemes mentioned above have a dynamic range of approximately 50 cm. However, a separate study has demonstrated that continuous level sensing via POF coupled with LEDs and PIN diodes can attain a greater dynamic range of 200 cm, albeit with a lower sea sensitivity of 12 mV/m [15].

This study aims to produce a POF sensor with LEDs and photodiodes capable of monitoring accurate, dependable, and economical water levels. To accomplish this, the sensor must meet certain criteria, including sensitivity and efficiency. The sensor underwent testing on the water at a depth exceeding 50 cm within a container.

2 Sensor Design

The plastic optical fiber utilized as the sensing component of the probe extends for a length of 300 cm, and the one as a probe is only 100 cm (see Figure 1). The probe is supported to maintain its shape and ensure it stays straight. Every 10 cm, the jacket and cladding components are opened, resulting in 20 sensing segments in the sensor probe. Whenever each sensing segment comes in contact with water, a voltage will be altered due to the optical fiber's power loss. The power loss of each exposed probe is measured through a light detector to determine the correlation between power loss and probe quantity. These 20 sections will subsequently denote the water level in the testing drum.

Stripping the jacket of a plastic fiber optic cable is accomplished with a custom knife and placemat tailored to the size of the cable diameter. The cladding is then removed via sanding using a mesh size of 1200. Test the cable by emitting laser light at one end to ensure complete cladding removal. If the light is uneven, the cladding layer is not thoroughly cleaned. Alternatively, the cladding wrapper may be opened using acetone liquid.

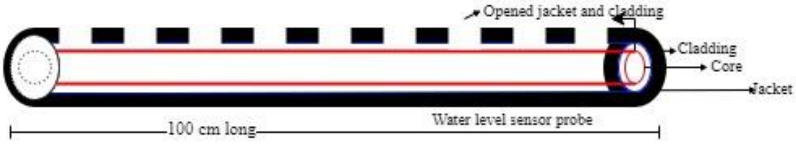

Fig. 1. Plastic fiber optic sensor probe.

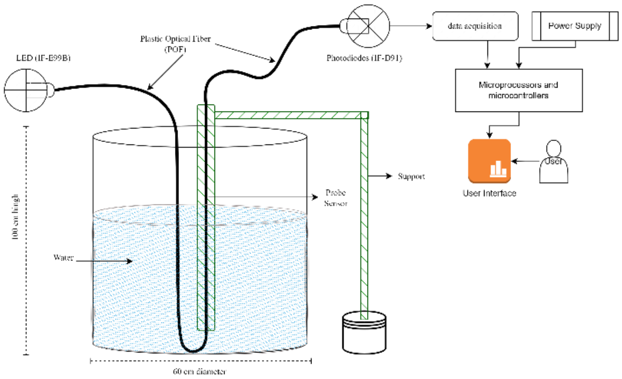

Fig. 2. Displays a U-shaped POF experiment illustrated in a schematic block diagram.

3 Material and Methods

Plastic Optical Fiber (type SK20) with a 0.5mm diameter was obtained from Mitsubishi Rayon Co., Ltd. The fiber's core comprises polymethylmethacrylate material and the cladding of fluorinated polymer material, with respective relative refractive indices of 1.49 and 1.41. Green LEDs and photodetectors (PDs) were procured from Digikey Inc. A data acquisition system (DAQ) with 16-bit resolution from National Instruments, USA, was utilized for photodetector acquisition.

The POF probe was formed into a U-shape measuring 3 meters in length. Subsequently, a plastic container, optoelectronic circuitry, DAQ, and water storage container were employed (see Figure 2). The plastic container was explicitly designed to accommodate the LED, two PDs, and POF probe. The circuitry for the LED and PDs operates on a 5-volt voltage source. This voltage signal is then sent to the DAQ, whereby the signal from the PDs is supervised with NI-DAQ.

The POF probes were placed in tubular glass containers with a drain valve at the bottom. The containers have a diameter of 60 cm and a height of 60 cm. A water pump was used to fill the container with water and adjust the liquid level as required. To prevent the formation of air bubbles during the test, the hose from the water pump was placed at the bottom of the container.

4 Results

The study aimed to evaluate the functionality of a fiber optic sensor for real-time monitoring of liquid level changes at a 55 cm height. The test entailed filling water into a container from 0 cm up to 55 cm at a volume rate of 3 mL/second for 8 minutes, followed by draining at a flow rate of 2 mL/second for 10 minutes.

Figure 3 displays the sensor response to the water level as plotted using the recorded voltage during the filling phase. Technical term abbreviations were explained when initially utilized.

The language used was formal, clear, concise, and objective, without biased or emotional language. It was discovered through the linear fit analysis that the sensitivity of the water level was 1.4 mV/mm within the 0-45 cm range and 3.3 mV/mm within the 45-55 cm range, resulting in voltage changes of 0.21 mm and 0.09 mm, respectively.

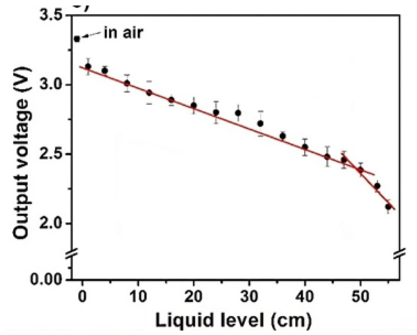

Fig. 3. Relationship between Sensor Output Voltage and Liquid Level.

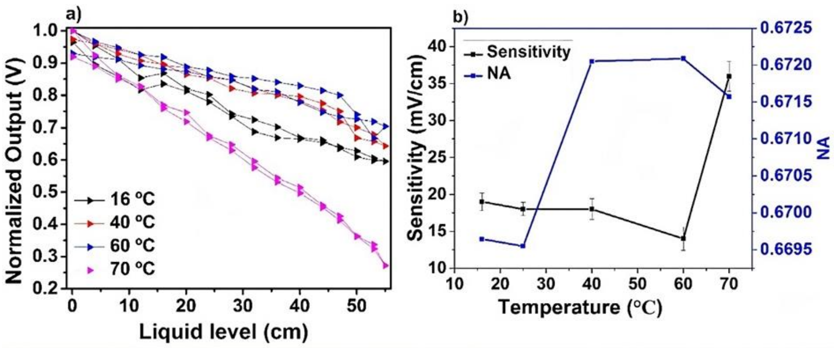

Fig. 4. displays (a) the relationship between normalized voltage, water level, and temperature variations at 16°C, 25°C, 40°C, 60°C, and 70°C. (b) Additionally, it illustrates the relationshin between temperature and sensitivity, which are 1.9, 1.8, 1.4, and 3.6 mV/mm, respectively.

Temperature variations can impact the refractive index of the liquid medium being observed, affecting the fiber optic sensor's level measurement. Additionally, changes in the liquid medium's temperature are expected to modify the refractive index of the optical fiber core, causing notable differences in both the core's NA and the liquid medium itself. POF can be utilized at temperatures below 80°C as per [16]. Therefore, we investigated the performance of POF at temperatures of 16, 25, 40, 60, and 70°C. Figure 4a illustrates the normalized sensor response during the water filling and draining phase, while Figure 4b compares the sensor's sensitivity under different water temperatures. The sensitivity gradually decreases as the temperature increases to 60°C, then abruptly doubles at 70°C. Under these conditions, the refractive index values of water fell from 1.33 to 1.32, and those of Polymethyl Methacrylate (PMMA) decreased from 1.49 to 1.487 363, as measured by an Atago PAL1 digital refractometer.

One limitation of optical sensors is their higher power consumption than sensors that use electrical sources, which poses a significant challenge, particularly in battery-powered devices. Therefore, an essential requirement for a level sensor is its ability to precisely measure the liquid level when activated, unaffected by previous changes. Figure 5 displays the sensor response during multiple on/off cycles in 30 minutes when the water level is set to 8, 44, and 55 centimeters. The device takes 60 seconds to stabilize after each activation. The experiment was repeated thrice to test the sensor's stability, and the response was recorded for 12 hours. The evaporation of water in the container caused an error of up to ±9mV (0.3% of the full-scale value of 3 V).

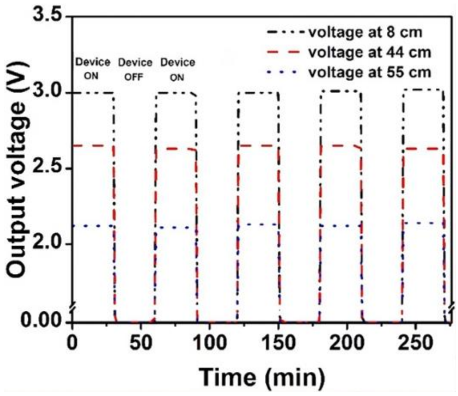

Fig. 5. Sensor response to changes in water levels was observed over four hours, during which the sensor was activated for 30 minutes, followed by a 30-minute deactivation period.

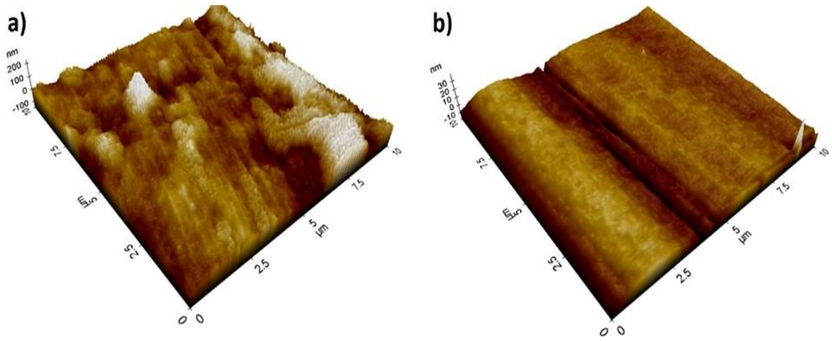

Fig. 6. displays the AFM images of (a) decladded POF and (b) bare POF.

5 Discussion and Conclusions

This research investigates the rise in optical power coupling at the photodiode in a water-level sensor based on polymer optical fiber (POF) as the liquid level rises. Technical abbreviations are explained at their first usage. A short POF was placed over a glass capillary and illuminated with a green light to study this phenomenon. Proper citation and formatting features were strictly adhered to while removing filler words. The results demonstrate a significant decrease in scattered light when the glass capillary is filled with water. This study contributes to the comprehension of optical phenomena in POF-based sensors for water level measurement, thereby aiding the development of more advanced sensor technologies.

This study aims to characterize the surface of POF that has been declassified and coated. Our observations using atomic force microscopy (AFM) indicate a sleeve roughness of approximately 80 nm on the declassified POF surface, whereas the bare POF surface is smooth (refer to Figure 6). This suggests that defects are present, which may cause light scattering on the uncoated fiber surface. Accordingly, we propose that the optical loss in POF-based sensors is due to light scattering. Previous research has explored POF-based refractive index (RI) sensors that utilize the phenomenon of reflected energy (EWA) with minimal light scattering. However, this study demonstrates that longer POF declassification times lead to increased scattering losses, which may arise from diverse declassification conditions.

The study observed an enhancement in sensitivity and range by 10-fold and 1.5-fold correspondingly. Despite the sensor's high-resolution capacity, a fiber optic level sensor with a straightforward and decoupled POF configuration is recommended for its ease and expediency. The proposed sensor's effective optical interaction with the fiber optic's surface and suitable optical power at the PD results in a superior signal-to-noise ratio. Optical intensity loss measurements are conducted using affordable LEDs and two photodetectors. The sensor provides an advantage in increased dynamic range for level measurement by selecting a larger diameter. Dynamic ranges of commercially available POFs up to 2.5 mm in diameter can be increased up to 5 times. These POF-level sensors can serve as sensitive point sensors using reference probes. The sensor suits various applications, including water and petroleum storage tanks.

Acknowledgments. This research is supported by the PNBP funds from Universitas Negeri Medan for the fiscal year 2023, by the decree of the head of LPPM UNIMED Number: 0138/UN33.8/KPT/PD/2023.

References

[1] Loizou and E. Koutroulis, "Water level sensing: State of the art review and performance evaluation of a low-cost measurement system," Measurement, vol. 89, pp. 204–214, Jul. 2016, doi: https://doi.org/10.1016/j.measurement.2016.04.019.
[2] H. H. P. Wu, C. W. Hung, S. H. Chang, and Z. H. Yang, "Analysis and Implementation of Noncontact Level Sensing for a Pressurized Cylinder," J Sens, vol. 2016, 2016, doi: https://doi.org/10.1155/2016/5027916.
[3] P. Li, Y. Cai, X. Shen, S. Nabuzaale, J. Yin, and J. Li, "An accurate detection for dynamic liquid level based on MIMO ultrasonic transducer array," IEEE Trans Instrum Meas, vol. 64, no. 3, pp. 582–595, Mar. 2015, doi: https://doi.org/10.1109/TIM.2014.2357586.
[4] B. Kumar, G. Rajita, and N. Mandal, "A review on capacitive-type sensor for measurement of height of liquid level," Measurement and Control (United Kingdom), vol. 47, no. 7. SAGE Publications Ltd, pp. 219–224, Sep. 08, 2014. doi: https://doi.org/10.1177/0020294014546943.
[5] C. Mou, K. Zhou, Z. Yan, H. Fu, and L. Zhang, "Liquid level sensor based on an excessively tilted fibre grating," Opt Commun, vol. 305, pp. 271–275, 2013, doi: https://doi.org/10.1016/j.optcom.2013.05.019.
[6] J. E. Antonio-Lopez, J. J. Sanchez-Mondragon, P. Likamwa, and D. A. May-Arrioja, "Fiber-optic sensor for liquid level measurement," Opt Lett, vol. 36, no. 17, pp. 3425–3427, 2011, doi: https://doi.org/10.1364/OL.36.003425.
[7] X. Liang, G. Ren, Y. Li, Z. Liu, H. Wei, and S. Jian, "In-fiber liquid-level probe based on Michelson interferometer via dual-mode elliptical multilayer-core fiber," J Mod Opt, vol. 63, no. 13, pp. 1254–1259, Jul. 2016, doi: https://doi.org/10.1080/09500340.2015.1137367.
[8] Y. Dong, S. Xiao, H. Xiao, J. Liu, C. Sun, and S. Jian, "An optical liquid-level sensor based on d-shape fiber modal interferometer," IEEE Photonics Technology Letters, vol. 29, no. 13, pp. 1067–1070, Jul. 2017, doi: https://doi.org/10.1109/LPT.2017.2700623.
[9] W. Lou, D. Chen, C. Shen, Y. Lu, H. Liu, and J. Wei, "An optical liquid level sensor based on core-offset fusion splicing method using polarization-maintaining fiber," in Journal of Physics: Conference Series, Institute of Physics Publishing, Feb. 2016. doi: https://doi.org/10.1088/1742-6596/680/1/012018.
[10] L. Bilro, N. Alberto, J. L. Pinto, and R. Nogueira, "Optical sensors based on plastic fibers," Sensors (Switzerland), vol. 12, no. 9. pp. 12184–12207, Sep. 2012. doi https://doi.org/10.3390/s120912184.
[11] N. Jing, C. Teng, J. Zheng, G. Wang, Y. Chen, and Z. Wang, "A liquid level sensor based on a race-track helical plastic optical fiber," IEEE Photonics Technology Letters, vol. 29, no. 1, pp. 158–160, Jan. 2017, doi: https://doi.org/10.1109/LPT.2016.2630730.
[12] H. Zhang et al., "Optical fiber liquid level sensor based on macro-bending coupling," Optical Fiber Technology, vol. 24, pp. 135–139, 2015, doi: https://doi.org/10.1016/j.yofte.2015.05.012.
[13] J. Park, Y. J. Park, and J. D. Shin, "Plastic optical fiber sensor based on in-fiber microholes for level measurement," Jpn J Appl Phys, vol. 54, no. 2, Feb. 2015, doi: https://doi.org/10.7567/JJAP.54.028002.
[14] P. Antunes, J. Dias, T. Paixão, E. Mesquita, H. Varum, and P. André, "Liquid level gauge based in plastic optical fiber," Measurement (Lond), vol. 66, pp. 238–243, 2015, doi: https://doi.org/10.1016/j.measurement.2015.01.030.

[15] F. Pérez-Ocón, M. Rubiño, J. M. Abril, P. Casanova, and J. A. Martínez, “Fiber-optic liquid-level continuous gauge,” Sensors and Actuators, A: Physical, vol. 125, no. 2. pp. 124–132, Jan. 10, 2006. doi: https://doi.org/10.1016/j.sna.2005.07.019.
[16] E. Mesquita et al., “Groundwater level monitoring using a plastic optical fiber,” Sens Actuators A Phys, vol. 240, pp. 138–144, Apr. 2016, doi: https://doi.org/10.1016/j.sna.2016.01.042.