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Fiber Optic Sensor Based on Lateral Offset Displacement for Water Quality Analysis in Agricultural Applications

Abstract. *In this study, we developed a fiber optic sensor based on a lateral offset displacement to evaluate the water quality of a hydroponic farming system. The fiber is set up in lateral offset SM-SM fiber mode. The fiber core has been spliced at a variety offset lengths, which serve as a sensing region of the fiber sensor towards the hydroponic crop system's water quality, including pH and temperature. Upon completion, the highest sensitivity was achieved by fiber optic sensor with an offset distance of 18.72 µm, with 0.1972 dBm/pH and 0.2863 dBm/°C for pH and temperature measurements, respectively.*

Streszczenie. *W tym badaniu opracowaliśmy czujnik światłowodowy oparty na czujniku przesunięcia bocznego do oceny jakości wody w systemie uprawy hydroponicznej. Światłowód jest ustawiony w trybie światłowodu SM-SM z przesunięciem bocznym. Rdzeń włókna został spleciony na różnych przesuniętych długościach, które służą jako obszar wykrywania czujnika włókna w kierunku jakości wody w systemie upraw hydroponicznych, w tym pH i temperatury. Najwyższą czułość uzyskano po zastosowaniu czujnika światłowodowego o odległości offsetu 18,72 µm, gdzie czułość uzyskana dla pomiarów pH i temperatury wynosi odpowiednio 0,1972 dBm/°pH i 0,2863 dBm/°C.* **(Czujnik światłowodowy oparty na przesunięciu poprzecznym do analizy jakości wody w zastosowaniach rolniczych)**

Keywords: fiber optic, hydroponic, lateral offset, optical sensor
Słowa kluczowe: światłowodowe, hydroponiczne, przesunięcie boczne, Czujnik optyczny

Introduction

The development of optical fiber sensors has progressed to the point where the technology's influence is now established. Fiber optic sensors have been used in a variety of applications due to the growing demand for sensor devices, such as in the medical, food, and agricultural industries [1] [2] [3] [4].

Currently, agriculture is emerging as a significant source of income. The hydroponic crop system is one of the most significant agricultural practices. Advanced sensor development is required to ensure continuous monitoring of the parameters of interest for the deployment of effective production cycles. Knowledge of soil water status, in particular, is one of the most important components for successful hydroponic management and plant development, and it is essential in the formulation of irrigation strategies to ensure the provision of water in the proper quantities and at the right time [5] [6]. Thus, it is critical in hydroponics to maintain water quality for pH and temperature in order to transfer nutrients to the plant. The ideal pH and temperature ranges for hydroponics are 5.0-7.0 and 18°C-28°C, respectively [7] [8].

Lateral offset displacement sensors have attracted a great attention in recent years because of its inherent simplicity, compact size, mobility, wide frequency capabilities, exceptionally low displacement detection limit, and ability to work without contacting the sample. The sensor's architecture in this research is based on a slight lateral offset of the sensing fiber, such that light from a lead-in fiber is spread into the core and cladding of the sensing fiber and detection is produced by the interaction of the cladding modes with the surrounding material [9] [10].

The goal of this project is to design and develop a device that can measure the water quality in a hydroponic agricultural system utilizing a Fiber Optic Sensor (FOS) and the lateral offset displacement technique. The lateral offset fiber sensor is spliced using a Single Mode-to-Single Mode (SM-SM) fiber configuration. The offset area serves as a sensing area for the fiber sensor, which will be submerged in the water of the hydroponic crop system to monitor temperature and pH.

Methodology

In this research, we designed and developed a fiber optic sensor based on a lateral offset displacement sensor for monitoring water quality (temperature and pH) in a hydroponic agricultural system. Single-mode fiber has been chosen as the main component. The fiber sensor probe was fabricated using a fusion splicing technique. Waist expansion and lateral offset structures are two types of fiber probe structures that can be developed by fusion splicing. The lateral displacement method was selected for this study because of its simplicity, as shown in Figure 1. Using this approach, the end surfaces of the fiber optic cable are aligned adjacent or abutting each other, parallel to their longitudinal axes. Lateral offset is the inability of the cross-sections of the two fiber cores to fully overlap, which cause power loss when transmitting light inside the fiber. Imperfections in the connections will have created a loss in light transmission, which is frequently manipulated as the sensing area in sensor design [11]. The light from a lead-in fiber, for instance, will be distributed into the sensing fiber's core and cladding, and therefore detection is established by the interaction of the cladding modes with the surrounding material [12]. The induced refractive index changes due to the core lateral offset displacement will lead to the variations of the optical output power [13].

Fig.1. Diagram of lateral offset displacement by splicing technique

The key procedure in the construction of sensing probes is fiber optic fusion splicing, which is performed using a SUMITOMO TYPE-36 fusion splicer. The fiber cladding and core each had a diameter of 125 µm and 10 µm. The misalignment that formed at the connections of two fiber ends served as the basis for the fiber sensor head, or sensing probe. Two distinct misalignment offsets of 11.57µm and 18.72µm were investigated in this study using single-mode fiber working around 1550 nm.The recorded pictures of the spliced offset segment from the splicing machine are presented in Figure 2 and Figure 3, as observed with the Axioskop 2 MAT Image Analyzer. The lengths of all fiber cables were set at 1 m.

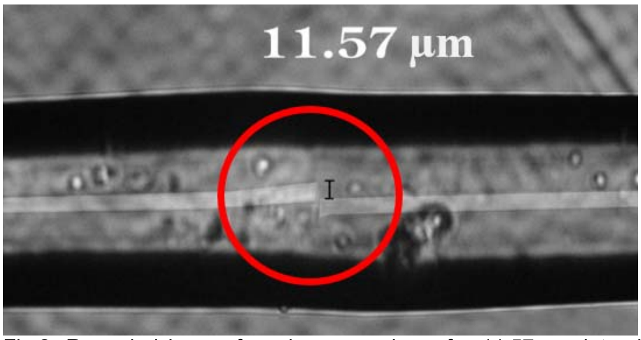

Fig.2. Recorded image from image analyzer for 11.57 µm lateral offset

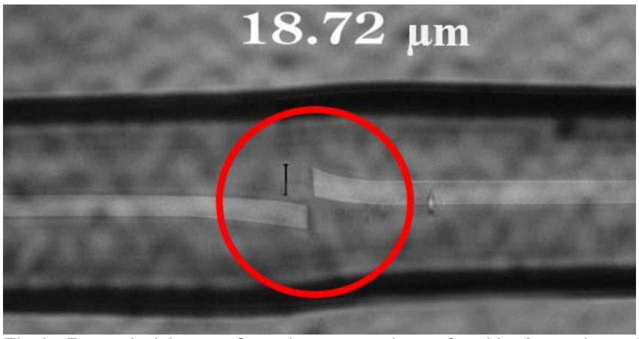

Fig.3. Recorded image from image analyzer for 18.72 µm lateral offset

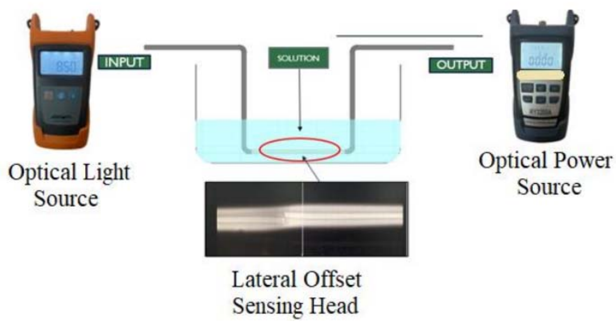

Fig.4. Experimental Setup

The experimental setup for measuring water quality is depicted in Figure 4. The fiber sensor's input was connected to an optical light source (OLS), and the sensor system's output was measured using an optical power meter (OPM). The sensor's sensing region was immersed in water samples to examine the sensing response to pH value and water temperature. The pH and temperature values of the water sample were then varied as shown in Table 1. Hydrochloric acid was used to increase the pH of a water solution, whereas Ammonium Acid to decrease the pH level. Room temperature was assumed.

Table 1: The pH and temperature setting

Parameter									
pH	4.5	4.9	5.4	5.6	5.9	6.4	6.6	7.0	7.5
Temperature (°C)	16	18	20	22	24	26	28	30	32

Results and Discussion

To study the effect of pH variations on the output power, 18 samples were prepared consisting of two different lateral offsets with 9 pH and 9 temperature setting as shown in Table 1. The range of pH and temperature was chosen based on the ideal range of these values for hydroponic application.

The correlation between pH value and refractive index unit (RIU) or 0 µm offset FOS is depicted in Figure 5. According to [14], the ratio of the refractive indices (RIs) of the core and cladding affects the angle of total reflection of light in a waveguide. Different pH values correspond to distinct RIs. Thus, it is abundantly clear from this study that the refractive index unit will increase as the pH value risen.

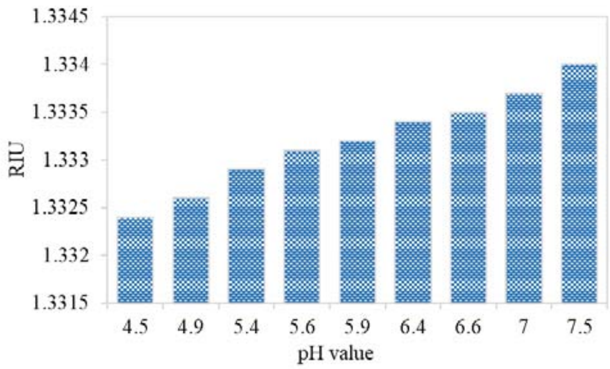

Fig.5. Refractive Index vs pH value

In order to study the effect of lateral offset variation to the sensor's performance, the offset of the tapered FOS was varied. Figure 6 shows the relationship between the pH value and output readings. The results can be related to previous research by [15] [16], showing similar trends where the power value decreased as the pH raised. Good linear response with a wide pH operation range was obtained. From the graphs, the steeper slope represents a higher sensitivity. The sensitivity of 0µm, 11.57µm and 18.72 µm offset is 0.086 dBm/pH, 0.123 dBm/pH, and 0.198 dBm/pH, respectively. Hence, it can be concluded that a longer offset has higher sensitivity.

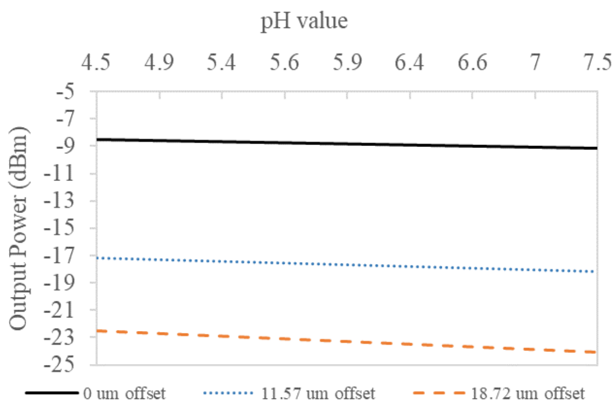

Fig.6. The Relationship between Output Power (dBm) and pH for SM-SM Fiber

The relationship between output power and temperature for three lateral offset settings is shown in Figure 8. It demonstrates that a longer lateral offset will result in a greater power loss [11]. As the temperature rises, the refractive index of hydroponic water decreases, resulting in increased power loss [17]. The findings is consistent with the Clausius-Mosetti equation, which states that as the RI increases, the output power decreases [18].

Figure 8 also depicts the findings, which reveal comparable patterns that can be related to previous work by [19]. A larger offset leads to sensitivity increment. The theory underlying the perfectly joined fiber end can be used to explain this. Since the two fiber ends are perfectly joined, the sensor probe has no misalignment for an offset distance of 0 m. As a result, it transmits light more effectively and experiences less fiber loss. Therefore, a fiber sensor with lower fiber loss has lower sensitivity. As a result, the signal's strength drops. Form the graph, the fiber sensor with a lateral offset of 18.72 µm outperformed the one with a lateral offset of only 11.57 µm in terms of sensitivity. The sensitivity achieved was 0.131 dBm/°C for 11.57µm and 0.286 dBm/°C for 18.72µm lateral offset displacement, respectively. With 0 µm offset, the sensitivity is 0.093 dBm/°C.

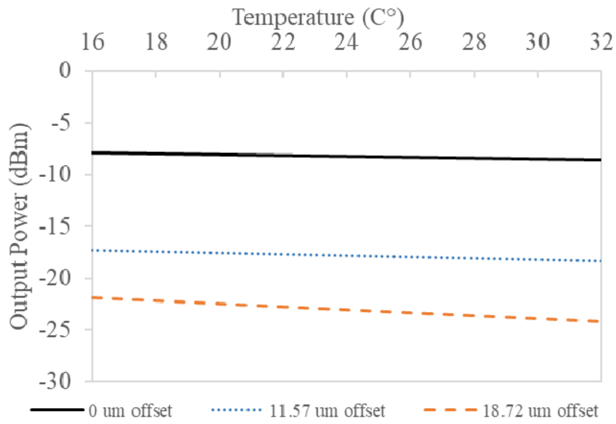

Fig.7. The Relationship between Output Power (dBm) and temperature for SM-SM Fiber

Figures 6 and 7 can be explained in the mathematical model that can be used to forecast sensor performance. In both diagrams, the general mathematical equation for the best linear fit line is:

$$y = mx + C \quad (1)$$

where *y* is output power, *x* is pH or temperature measured and *C* is the intercept of the graph. The mathematical modelling for the sensor performance in measuring the pH and temperature value is listed in Table 2, based on 18.72 µm lateral offset. The presented mathematical model is simple and can be as reference in the optical sensor development for various applications.

Table 2: Mathematical expression for pH and temperature sensing based on lateral offset optical sensor

Parameter	Mathematical Expression
pH	y = -0.198x - 22.306
Temperature (°C)	y = -0.2863x - 21.623

Conclusions

In this study, we developed and tested a simple and highly sensitive fiber sensor based on SM-SM lateral displacement technique for agricultural applications. Two lateral offset setting have been tested, which is 11.57 µm and 18.72 µm to test the sensor's responses towards temperature and pH value. Upon completion, it was discovered that the 18.72 µm lateral offset sensor is more sensitive to temperature and pH changes in the ranges of 16°C-32°C for temperature and 4.5 to 7.5 for pH value, which are the ideal ranges for agricultural applications. The 18.72 µm lateral offset sensor has the sensitivity 0.1972 dBm/pH and 0.2863 dBm/°C, for pH and temperature, respectively.

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REFERENCES

[1] Leona M., Consales M., Passeggio G., Buontempo S., Zaraket H., Youssef A., Persiano G.V., Cutolo A., Cusano A., Fiber optic soil water content sensor for precision farming, *Optic & Laser Technology*, 149 (2022), nr 107816, 1-11

[2] Matsuura Y., Lasers for Medical Applications, *In Woodhead Publishing Series in Electronic and Optical Materials*, Woodhead Publishing, 2013, 110-124.

[3] Idris S.K. Haroon H. Abdul Razak H. Mohd Zain A.S., Investigation on fiber optic sensor using FBG for various temperature and liquid density, *Journal of Physics: Conference Series*, 1502 (2020), Issue 117, In International Conference on Telecommunication, Electronic and Computer Engineering 2019, ICTEC 2019.

[4] Haroon H., Nordin S.N., Rahim H.R.A., Anbalagan T., Othman M., Examination of adulterated coconut oil by fiber optics displacement sensor using lateral offset approach, *Jurnal Teknologi,* 84 (2022), Issue 5, 185 – 190.

[5] Singh H., Dunn B., Payton M., Hydroponic pH Modifiers affect Plant Growth and Nutrient Content in Leafy Greens, *J. Hortic. Res.*, 27 (2019), nr. 1, 31–36.

[6] Raghul S., Sribalaji B. V., Vishnubalan K., Velu A., Auto Hydroponic Growth Chamber for Precision Agriculture, *International Journal of Innovative Research in Science, Engineering and Technology*, 10 (2021), nr. 6, 6057-6060.

[7] Parks S., Murray C., Leafy Asian vegetables and their nutrition in hydroponics, *Clin. Exp. Dermatol.*, 31 (2006), nr. 3, 361–364, 2006.

[8] Griffiths M., The Design and Implementation of a Hydroponics

Control System, Master Thesis, Oulu University of Apllied Sciences, 2014.
[9] Spillman W. B., Udd E., Connectors and Splices," *F. Guid. to Fiber Opt. Sensors*, 2015, 1–12,
[10] Duan D.W., Rao Y. J., Xu L.C., Zhu T., Wu D., Yao J., In-fiber Mach-Zehnder interferometer formed by large lateral offset fusion splicing for gases refractive index measurement with high sensitivity, *Sensors Actuators B Chem*., 60 (2011), nr. 1, 1198–1202.
[11] Haroon H., Nordin S.N., Anbalagan T., Othman M., Edible oils adulteration analysis by fibet optic multimode displacement sensor, *Optoelectronics and Advanced Materials - Rapid Communications*, 16 (2022), nr. 1, 36-40.
[12] J. Liu *et al.*, "A wide-range displacement sensor based on plastic fiber macro-bend coupling," *Sensors (Switzerland)*, 17 (2017), nr. 1, 1–8, 2017.
[13] Niu H. et al., Optical fiber sensor based on core-offset structure: A review, *IEEE Sens.J.*, 21 (2021), nr. 20, 22388-22401.
[14] Baharin N.F., Azmi A.I., Abdullah A.S., Mohd Noor M.Y, Refractive index sensor based on lateral-offset of coreless silica interferometer, *Opt. Laser Technol*., 99(2018), 3986-401.
[15] A. El Hamidi *et al.*, "Refractive index controlled by film morphology and free carrier density in undoped ZnO through sol-pH variation," *Optik (Stuttg).*, vol. 158, pp. 1139–1146, 2018, doi: 10.1016/j.ijleo.2018.01.011.
[16] Wang S., Zhang D., Xu Y., Sun S., Sun X., Refractive Index Sensor Based on Double Side-Polished U-Shaped Plastic Optical Fiber, Sensors, 20 (2020), nr. 18, 5253.
[17] Alawsi S. M. K., Jabbar M. A., Refractive Index and Temperature Sensor Using HC-1550 Infiltrating by Different Liquid Crystal, *Opt. Photonics J.*, 08 (2018), nr. 03, 29–39.
[18] Haroon H., Kareem A., Statistical analysis on impact of temperature to Fiber Bragg Grating sensor performance, 13 (2019), nr. 5-6, 290-294.
[19] Haroon H., Nordin S. N., Abdul Rahim H.R., Anbalagan T., Othman M., Examination of adulterated coconut oil by single-mode fiber optic sensor using lateral offset approach, Jurnal Teknologi, 84(2022), nr. 5, 185-190.