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Development of a Low Cost Planar Interdigital Ammonia Sensor for Water Quality Sensing Application – Prototype

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ABSTRACT

Contaminated water does not only affect human beings, but the life of aquatic species also relies on clean water. Critical parameters such as dissolved oxygen (DO), the potential of hydrogen (pH), ammonia, nitrate and also temperature must be observed. Ammonia is toxic to fish and can be damaging to any fish production system. This paper presents three types of planar interdigital sensors that have been fabricated and developed for the aim of the aquaculture monitoring process. The objectives of this study are to develop and to characterize a sensor suitable for ammonia detection for aquaculture application; to evaluate the effectiveness of the sensor to detect the ammonia level in the water and also to develop a low cost ammonia sensor. There are several experiments conducted on these planar interdigital sensors to recognize which sensor produces a better sensitivity. These planar interdigital sensors are designed with the same number of positive electrodes but different numbers of negative electrodes. The experiment was carried out by using Impedance Analyzer IM3570 to obtain the data and NI myRIO-1900 was used to monitor the sensor application. Wheatstone bridge was used as signal conditioning to interface between the sensor and NI myRIO-1900. Graphical User Interface (GUI), programmed using LabVIEW was developed to interface between the hardware and the software parts. Results show that Sensor 1 has the best sensitivity compared to other sensors.

Keywords: *Planar interdigital sensor; Ammonia; Aquaculture; NI myRIO-1900; LabVIEW.*

1. INTRODUCTION

A healthy and clean living environment is vital to food, the environment, human health and human bodies. Nowadays, the low quality of water can be dragged into a massive issue for our society. Polluted water can cause contagious diseases such as diarrhea, cholera, and typhoid [1]. Contaminated water does not only affect human beings but aquatic animals such as fish as a source of protein for a human can be affected too.

Moreover, the life of aquatic species also relies on clean water. The quality of freshwater resources is affected by environmental pollution that triggered the effort to develop a water quality monitoring system to monitor critical parameters such as dissolved oxygen (DO), the potential of hydrogen (pH), ammonia, nitrate and also temperature. These parameters must be

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constantly measured and handled in order to get a better quality of water [2]. Study shows that freshwater aquaculture is low cost compared to mariculture [3]. However, freshwater aquacultures are facing a problem with regards to the poor conditions of water quality than mariculture because the species are living in small areas such as ponds which have high density.

Specifically, a high concentration of ammonia can build the development of green growth and amphibian plants. It is understood that ammonia is toxic to fish and can be damaging to any fish production system. Thus, the ammonia level is crucial in the aquaculture industry. The main source of ammonia is simply through the fish excretory product. The excrement rate is immediately connected to the encouraging rate and the protein level in the bolster being utilized [4]. The increases in ammonia caused by fish are due to the behavior of fish during stress and exhaust conditions [3].

The only way to know the existence of ammonia is by testing the water. This is because ammonia itself is colorless with a characteristically pungent smell. The concentration of 2 mg/L or above of un-ionized ammonia in water can be poisonous to fish [5]. The rise of concentration of ammonia (100 mg/L or over) in water can lead to the death of the human as well as aquatic life [5]. Although an ammonia sensor is available in the market, it is costly and unaffordable to most of the local fish breeders. Thus, they opt for a cheap solution to monitor the ammonia level in their fish tank.

The development of a new low-cost sensor is needed in order to provide reliable data for the ammonia contamination in the water [6]. The planar interdigital sensor working principle is essentially based on the two parallel plate capacitors rule. The electrodes are facing upwards in order to produce a one-sided approach to the material under test (MUT) [3]. Theoretically, a planar interdigital sensor was used as a sensing platform for biosensors and chemical sensors for different applications [7]. Hence, the design of the planar interdigital sensor is focused on the objective to determine the impedance value of the chemical sensor and impedimetric biosensors. Thus, in order to maintain the ammonia level at the allowable range set by the Fisheries Research Institute Malaysia (FRI), the development of a new planar interdigital sensor which is low cost is compulsory.

2. METHODOLOGY

2.1 Planar Interdigital Sensor

Nowadays, the use of sensor technology to measure the chemical content in a liquid is vital to any industries including aquaculture industries. There are lots of methods that have been used to analyze and detect the level of ammonia in water. The methods that had been employed include spectrophotometric based on the Berthelot reaction, potentiometric electrodes, amperometric, flow spectrometric and infrared (IR) absorption [8]. However, every one of these methods has its own advantages and disadvantages [9].

A prior study also shows that a planar interdigital sensor can also be applied to detect the ammonia level [9]. The advantage of using this planar interdigital sensor is because the cost is inexpensive compared to other methods [9]. Thus, a new low-cost sensor is developed by using the planar interdigital model. This newly developed sensor is designed by using Proteus software and fabricated by using a single-sided printed circuit board (PCB) fabrication technology. The characteristic of the planar interdigital sensor can be employed for liquid

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measurements by measuring its electrical properties. The capacitance value depends on the length of width space and the concentration of liquid to be measured [9].

Other than that, the operating principle of this planar interdigital sensor is essentially complying with the rule of two parallel plate capacitors [10]. The impedance value of the sensor will change because of the electromagnetic field resulting between the positive and negative plates of the sensor. The sensor acts as a capacitor in which capacitive value turns into a function of the system properties [11].

2.2 Sensor Development

This planar interdigital sensor was designed by using Proteus 8 and it has been fabricated by using a single-sided PCB where the thickness used was 0.25mm. There are three sensors that have been developed and fabricated. Each of the sensors is having the same effective area of 30mm by 40mm and having fringing (the area between two electrodes) of 2.5mm. The positive and the negative electrodes are having an equal length and width of 30mm and 30mm severally. This planar interdigital sensor was designed by reviewing the calculation based on the previous study.

These sensors were designed for having an equal number of electrodes. The capacitance value can be obtained by calculating using the given formula in equation (1). The d (the spacing between 2 adjacent negative and positive electrodes which create the capacitance) was influenced by the number of negative electrodes. Thus, the more the number of negative electrodes, the higher the value of d. Sensor 1 was designed to have two positive electrodes at the end and separated by eleven negative electrodes while Sensor 2 was designed to have three negative electrodes between two positive electrodes and Sensor 3 has one negative electrode between two positive electrodes. Figure 1 shows the design of the planar interdigital sensors while Figure 2 shows the fabrication of the low cost planar interdigital sensor.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{1}$$

where:

C is the capacitance (F)

ε_0 is the permittivity of free space (8.854×10^{-12} F·m^{-1})

ε_r is the dielectric constant (vacuum) (1)

A is the effective area (m^2)

d is the effective spacing (M)

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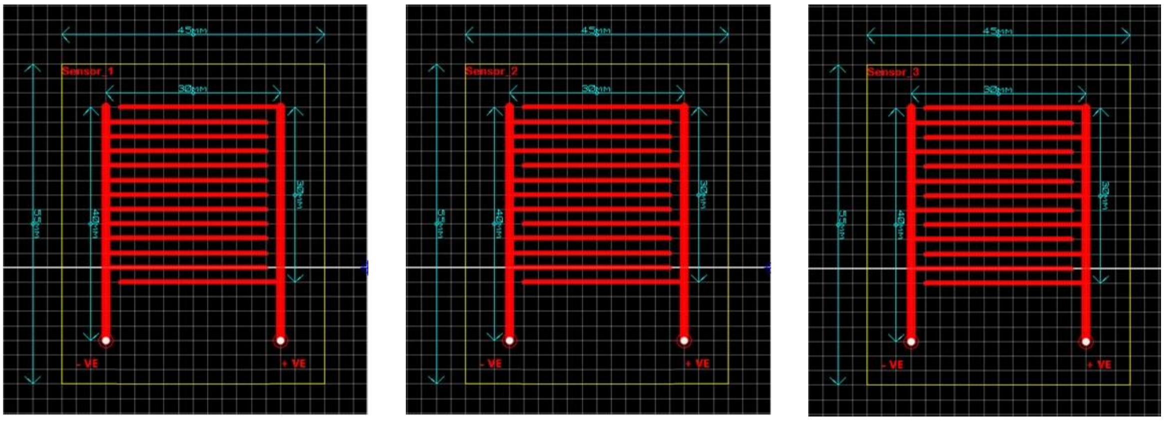
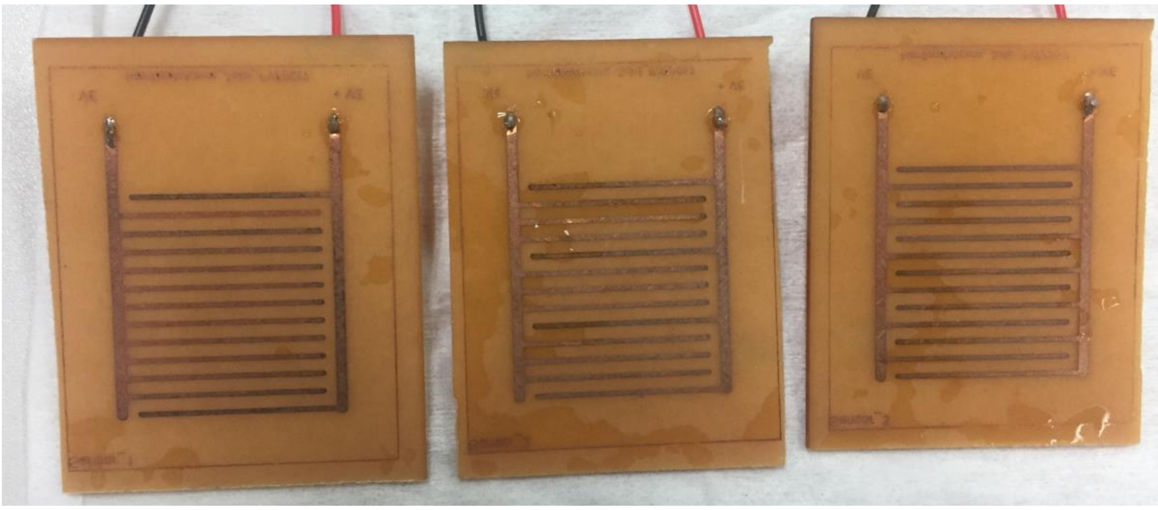


Sensor 1 Sensor 2 Sensor 3

Figure 1: 3 planar interdigital sensors with an equal number of electrodes were designed with different topologies of coupling the negative electrodes with positive electrodes.



Sensor 1 Sensor 2 Sensor 3

Figure 2: The fabricated planar interdigital sensors.

2.3 Characterization of the Sensor for Design

The total impedance of the sensors can be calculated to determine the characteristic of the sensor at different frequencies between 1 kHz to 100 MHz when material under test (MUT) is aired. The characterization of the sensor on its impedance characteristic has been done by using an Impedance Analyzer, IM3570. Two parameters have been measured, impedance value (Z) and phase value (°). Several experiments were conducted by using different types of MUT such as deionized water, sample water (lake water) and ammonium chloride. The Impedance Analyzer IM3570 was connected to a computer and impedance and phase values were recorded and calculated by using LCR Meter Sample Analysis.

Figure 3 shows the experimental set up for different MUT experiments. The experiment is conducted to determine the characteristic of the sensor in terms of impedance characteristic on the sensor's capacitive characteristic. The frequency is in the range of 1 kHz to 100MHz while the supplied constant voltage (CV) is in the range of 1V to 5V. The frequency value was chosen

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in that range to analyze the changes in impedance and phase due to the different frequency value injection while the voltage value range is between 1V to 5V because NI myRIO-1900 are having a maximum of 5V injection voltage. Air and deionized water were used as a reference for the calibration process. Sample water from the pond was taken as part of the experiment set-up. Several tests on the different concentrations of chemicals also had been conducted in order to test the stability of the developed sensor. The chemical used was Ammonium Chloride (NH_4Cl) with the concentration used is between 0.1mg/L to 0.5mg/L.

Once the impedance is gathered, Z value, the real part (R) and the imaginary part (capacitive reactance, Xc) can be referred to:

$$X_C = Zsin\theta \tag{2}$$

$$R = Zcos\theta \tag{3}$$

Later, the effective capacitance can be calculated:

$$C = \frac{1}{2\pi f X_c} \tag{4}$$

where f is a frequency in Hz.

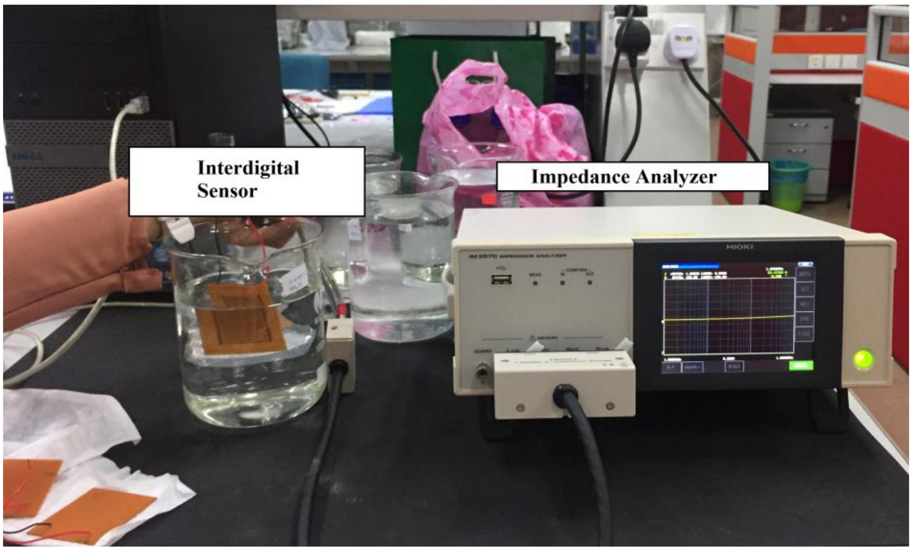

Figure 3: Experimental set up during the characterization process of developed planar interdigital sensor.

2.4 Sensor Application for Low Cost Commercialization

A data acquisition system (DAQ) will be used to test the effectiveness of these sensors. DAQ was chosen based on the equipment available in the research area. Fortunately, Aquatech Bio Resources laboratory is already equipped with LabVIEW and NI myRIO. Figure 4 shows the flowchart for the overall set-up during the application process. The water sample is taken from the aquaculture industry during the process. The sensor is then being submerged into the sample and the data will be gathered by using LabVIEW. Later, the result was then recorded and displayed.

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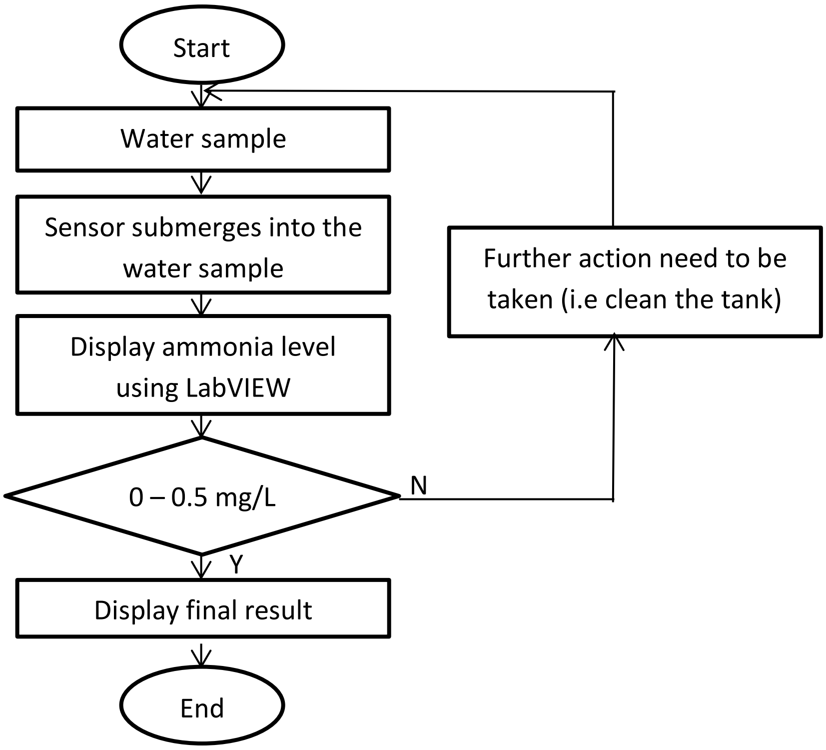

Figure 4: Flowchart of the system operation.

The DAQ NI myRIO-1900 is employed as an interface between the sensor and the computer. Furthermore, this device is Wi-Fi enabled which grants users fast and easy integration. Data measured by the sensor will be transferred through Wi-Fi using the DAQ to the monitoring station. A LabVIEW is used to analyze the gathered data.

2.5 Signal Conditioning Circuit

As these planar interdigital sensors produce impedance values, a Wheatstone bridge circuit was developed in order to convert to voltage before connecting to the DAQ. Theoretically, the Wheatstone bridge is used in signal conditioning in order to detect any changes in resistance value in terms of voltage variation [12]. Figure 5 shows the developed bridge circuit for this project where R1 and R2 are set to 1kΩ. While R3 is a variable resistor and R4 is an active resistor (sensor).

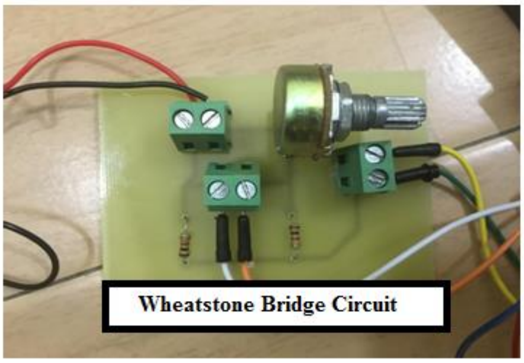

Figure 5: Wheatstone bridge circuit.

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2.6 Experimental Set Up for the Low-Cost Sensor

Figure 6 shows the experimental set up for the application used. The supply voltage of 5V from the NI myRIO-1900 had been injected to the positive terminal of the Wheatstone bridge circuit as a power supply while the negative terminal of the circuit was connected to the Ground from the NI myRIO-1900. The Wheatstone bridge circuit was then connected to the input of the NI myRIO-1900 at the AI1+ and AI1- port. Prior study shows myRIO is a better device to be used because of its real-time performance and customization of I/O. The data was collected, analyzed, and displayed on the computer using LabVIEW.

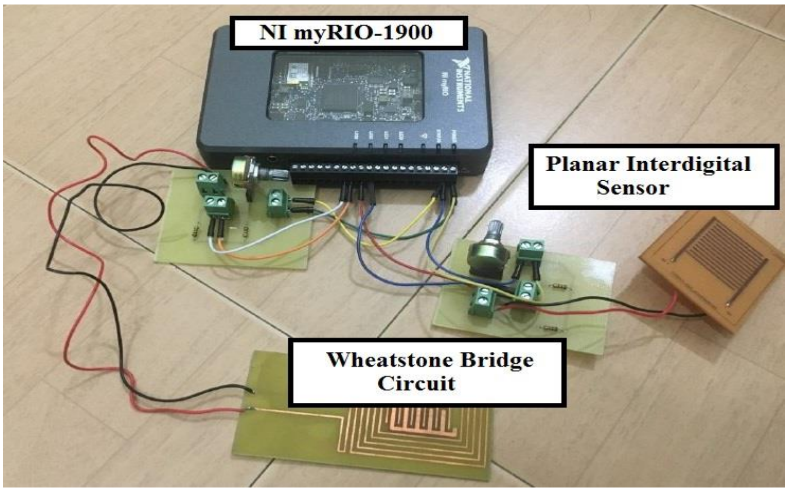

Figure 6: Experimental set-up for the prototype of ammonia sensor.

2.7 Conventional Method

Currently, most of the fish breeders opt for a cheap method in identifying the level of ammonia in the fish pond. Thus, a conventional method was used to determine the ammonia value based on the color changing of the water. 10 sample readings were taken and for each sample, 8 drops of both Test Solution (Bottle #1 and Bottle #2) were dripped into the water sample. Figure 7 shows the solution test that was used in this experiment while Figure 8 shows the Test Kit Table used to identify the ammonia value based on the color changing of sample water.

Figure 7: Ammonia test solution.

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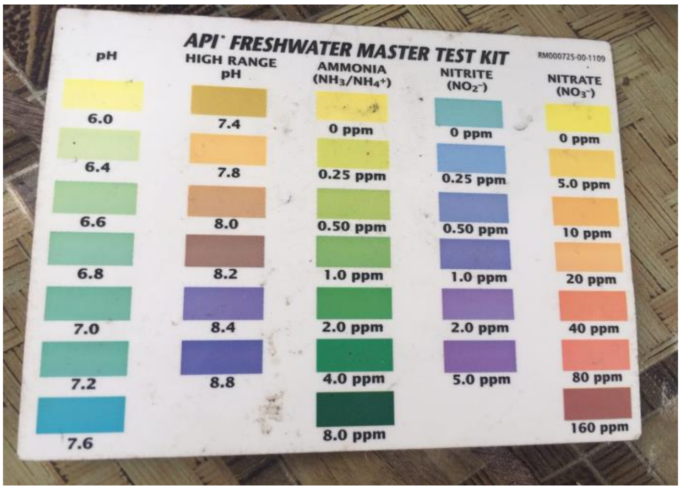

Figure 8: Freshwater master test kit table.

3. RESULTS AND DISCUSSION

The experiments were conducted to obtain the impedance characterization for the selected sensor as mentioned in section II. The results obtained were in data numbering form and converted into graph form. Based on these experiments conducted, the best sensor has been determined and will be discussed in section IV. Furthermore, the water sample was taken from the aquaculture industry in Tasek Gelugor. The results were then compared to the Fisheries Research Institute of Sayak Island (FRI) to fulfill the requirement.

3.1 Characterization of the sensors via laboratory testing

Figure 9 shows the relationship between air and developed sensors. From the data obtained, it clearly shows that the impedance curve for Sensor 1 seems to be steeper compared to Sensor 2 and Sensor 3. It is also shown that sensor 1 has the highest impedance value and the capacitive part starts to be invisible around 100 kHz.

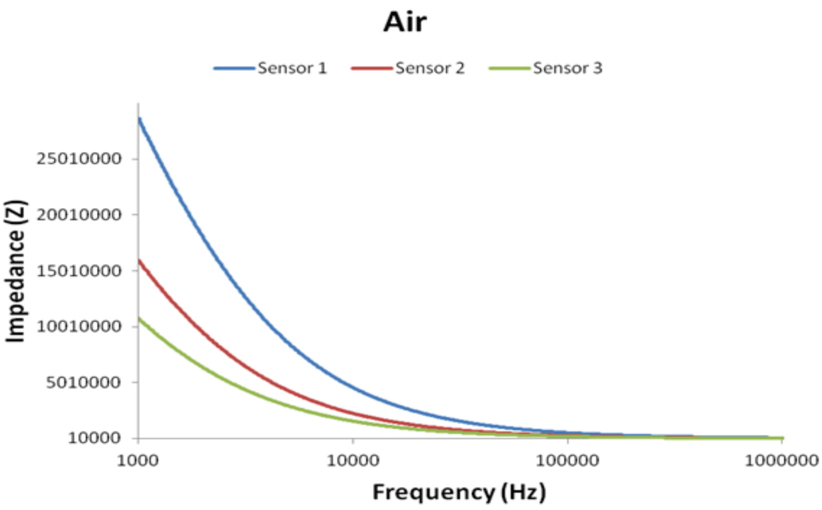

Figure 9: Impedance (Z) curves between 3 developed sensors

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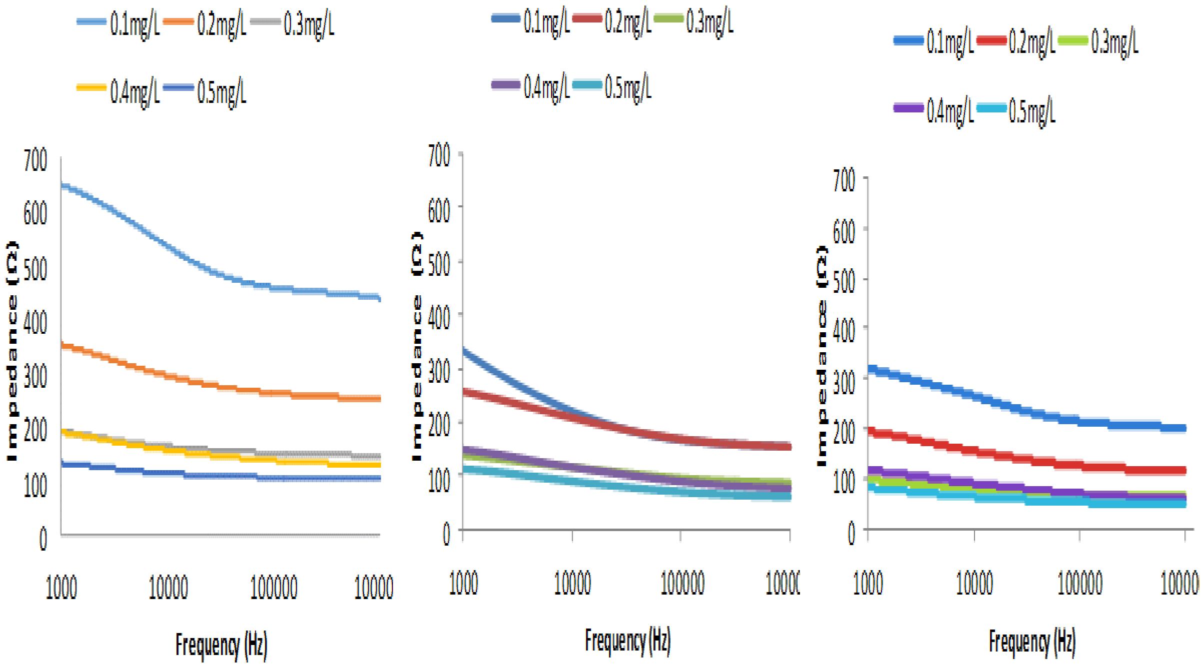
3.2 Experiments with Chemical Based Ammonia (Ammonium Chloride)

Figure 10 shows a relationship between the sensors and the different concentrations of Ammonia samples in the form of Ammonium Chloride (NH4Cl). The concentration of the Ammonia was measured in mg/L (milligram per Liter) instead of PPM (pipe per million) with the values of the concentrations being 0.1, 0.2, 0.3, 0.4 and 0.5 mg/L respectively. It can be seen that the range of the impedance values gathered from Sensor 1 is in the region of 100Ω to 700Ω. Whereas, sensor 2 shows a slight decrease in the range of impedance values that is from 100Ω to 400Ω. Subsequently, sensor 3 shows a much lower impedance which is from 50Ω to 350Ω. Based on these three graphs, it can be concluded that sensor 1 has the highest impedance value compared to sensor 2 and sensor 3. This is due to the uniformity in terms of electric field intensity distribution and capacitance within sensor geometry.



Sensor 1 Sensor 2 Sensor 3

Figure 10: Sensors vs different concentrations of Ammonium Chloride

3.3 Experiments with Chemical Based Ammonia (Ammonium Chloride) and Deionized Water

Figure 11 shows the real and imaginary part sensitivity. In this experiment, a frequency of 10 kHz has been used. It can be seen that the real part sensitivity value for all sensors is in the negative region. This is because of the rising conductivity in the solution while the imaginary part is in the negative region due to the sensor's characteristics. Study shows that the operating principle of this planar interdigital sensor essentially complies with the rule of two parallel plate capacitors as based on Smith Chart, the capacitance must be in the negative region of the chart [12]. Sensor 1 displays the highest sensitivity of the real and imaginary parts.

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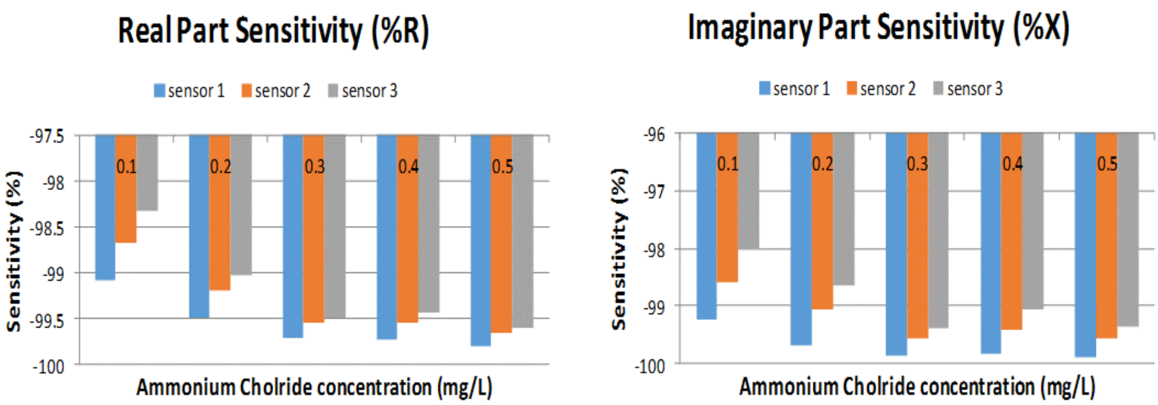

Figure 11: Real and imaginary part sensitivity of each sensor

3.4 Experiment with Chemical Based on Ammonia and Water Sample for Application Purposes

Table 1 shows the data obtained from the experiment involving the chemical based on ammonia and sample water. This table tabulates the ammonia reading gathered from the conventional method and voltage value obtained using a planar interdigital sensor. It can be seen that as the ammonia value reaches above 1, the voltage obtained is negative. This is because, if an increase in one variable tends to be associated with a decrease in the other then this is known as a negative correlation. This finding supports Figure 10 where the graphs have shown that the higher the concentration of Ammonia the lower the value of the impedance. Note that the sensor's initial characterisation is based on ammonium chloride concentrations of 0.1 to 0.5 mg/L, which could theoretically alter the voltage reading if the ammonia measurement exceeds 0.5 mg/L. The trend, however, indicates that a higher ammonia level will result in a lower resistance value. Hypothetically, higher ammonia levels will result in higher voltage readings. Further analysis needs to be made with a higher concentration levels of ammonium chloride during the characterization stage.

Table 1. Results on the ammonia reading based on voltage obtained

Voltage (V)	Ammonia (mg/L)
0.77	0.25
1.63	0.5
-1.20	1
-1.36	1
1.13	0.25
1.03	0.25
1.25	0.25
1.60	0.5
1.63	0.5
-2.56	2

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Figure 12 illustrates a relationship between voltage from the sensor and ammonia value from the conventional methods. It can be clearly seen that the correlation was very weak with R=-0.05. It may be due to the fact that using a conventional method in determining the level of the ammonia, it can be very subjective as it totally relies on the observation of the color of the water sample after 5 minutes. Results from conventional methods can be argued and highly dependent on the operator itself. Thus, it affects the conclusion of this study. Based on the experiments conducted, it is found that sensor 1 has the best performance among these 3 sensors. Furthermore, sensor 1 has the highest number of negative electrodes compared to sensors 2 and 3. This finding is in line with the previous study that the more the number of negative electrodes indicates the higher the sensitivity of the sensor [12].

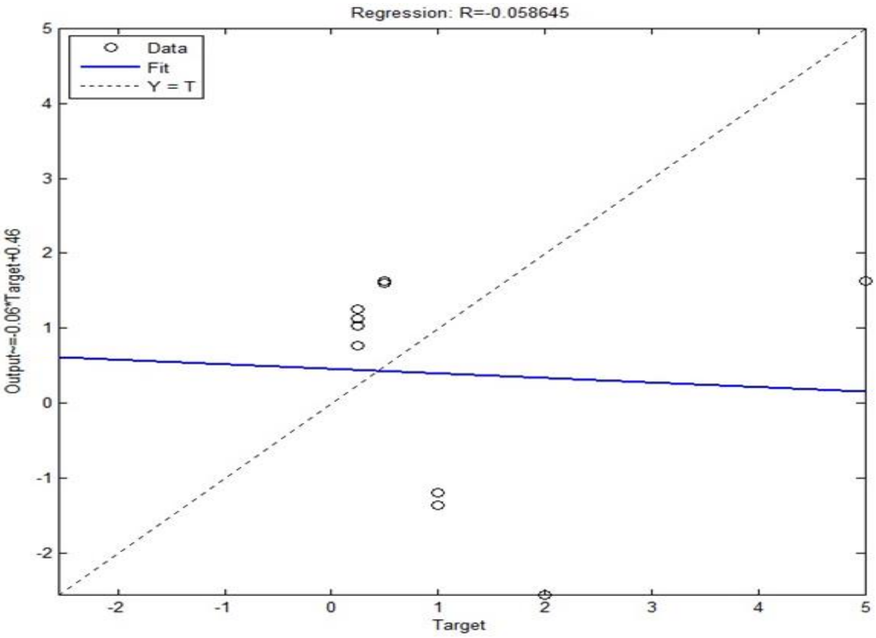

Figure 12: Correlation graph between voltage value vs ammonia value.

4. CONCLUSION

Three types of planar interdigital sensors have been developed and evaluated. Results show that a higher number of negative electrodes is crucial during designing a good planar interdigital sensor. The results from the study conducted show that this planar interdigital sensor can be applied for the detection of unsafe ammonia contamination in water. This sensor can be used as a tool for aquaculture monitoring in the pisciculture farm where the ammonia level should not exceed 0.5mg/L. Thus, based on the development results, Sensor 1 has been chosen as the sensor for the application. Although the objectives of this study were achieved, more tests and comparisons on a larger scale with an accurate sensor are proposed in order to determine the accuracy and stability of this new developed planar interdigital sensor.

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REFERENCES

[1] S. Abhinav, S. Srinivasan, A. Ganesan, M. Anala, and T. Mamatha, "Wireless water quality monitoring and quality deterioration prediction system," in *2019 26th International Conference on High Performance Computing, Data and Analytics Workshop (HiPCW)*, pp. 23-28, 2019.

[2] T. Ajmal, T. K. Anyachebelu, M. Conrad, and D. M. Rawson, "Evaluating urban surface water quality in Luton," *Environmental monitoring and assessment*, vol. 191, pp. 147, 2019.

[3] S. N. R. Kamisetti, A. D. Shaligram, and S. Sadistap, "Smart electronic system for pond management in freshwater aquaculture," in *2012 IEEE Symposium on Industrial Electronics and Applications*, pp. 173-175, 2012.

[4] M. A. M. Yunus, "Planar Electromagnetic Sensors for Environmental Monitoring," Massey University, 2011.

[5] Y. M. Chung, Z. A. Halim, and R. Raffay, "Un-ionized ammonia detection system for water quality monitoring," in *2012 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, pp. 274-279, 2012.

[6] T. Abel, B. Ungerböck, I. Klimant, and T. Mayr, "Fast responsive, optical trace level ammonia sensor for environmental monitoring," *Chemistry Central Journal,* vol. 6, pp. 1-9, 2012.

[7] N. A. Othman, N. S. Damanhuri, M. A. S. Mazalan, S. A. Shamsuddin, and M. H. Abbas, "Automated water quality monitoring system development via LabVIEW for aquaculture industry (Tilapia) in Malaysia," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 20, pp. 805-812, 2020.

[8] M. A. M. Yunus and S. Mukhopdhyay, "A new method for monitoring ammonium nitrate contamination in natural water sources based on independent component analysis," in *SENSORS, 2011 IEEE*, pp. 1066-1069, 2011.

[9] S. Boonkirdram and W. Sa-Ngiamvibool, "A novel planar interdigital capacitor level sensor," *Przegląd Elektrotechniczny,* vol. 91, pp. 91--95, 2015.

[10] N. Afsarimanesh, S. C. Mukhopadhyay, and M. Kruger, "Planar interdigital sensors and electrochemical impedance spectroscopy," in *Electrochemical Biosensor: Point-of-Care for Early Detection of Bone Loss*, ed: Springer, pp. 33-44, 2019.

[11] A. M. Syaifudin, M. Yunus, S. Mukhopadhyay, and K. Jayasundera, "A novel planar interdigital sensor for environmental monitoring," in *SENSORS, 2009 IEEE*, pp. 105-110, 2009.

[12] J. Karki, "Signal Conditioning Wheatstone Resistive Bridge Sensors," *Applications Report, Texas Instruments. SLOA034*, pp. 1-4, 1999.

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