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Planar Sensors Array for Water Contaminants Detections

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ABSTRACT

Planar electromagnetic sensors are widely used in many applications due to its low cost, simple architecture, and fast response. Currently, there are many types of membranes which have been introduced to remove contaminants from an aqueous solution. Hence, the water quality could be maintained and safe to consume. The objective of this paper is to apply and investigate the effectiveness of a selective membrane in detecting nitrate, phosphate, zinc, and nickel ions by means of planar electromagnetic sensors array (PESA). The samples have four different concentration levels, 5 ppm, 25 ppm, 75 ppm, and 100 ppm. The selective membrane's performance is evaluated based on absolute average sensitivity (|Z%|). This performance is compared with conventional coating such as incralac. The developed membrane consists of two elements which are polymer and solvent. Modified silica is selected as a polymer material while N-(2-Aminoethyl)-3 Aminipropyltrimethoxysilane is selected as a solvent. The selection of these materials is based on their ability to attract the contaminants in the aqueous solution and hence increased the selectivity. The proposed sensor with a membrane shows its higher sensitivity compared to incralac. The highest sensitivity is 338 % which observed in the presence of membrane for the nickel detection. Meanwhile, the lowest sensitivity using membrane is 12 % for zinc detection.

Keywords: Planar electromagnetic sensor array, water contaminants, star configuration, water supply quality

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INTRODUCTION

Tremendous developments in the agricultural and industrial sectors have directly affected the water supply quality. Agricultural activities, farm animals, and industry are the primary causes for increases in non-metallic impurities in water resources. These impurities or foreign substances may contain

various diseases and therefore dangerous to humans. A high concentration of nitrate in drinking water can lead to gastric cancer, blue baby syndrome, and Parkinson's disease (World Health Organization, 2011). For instance, zinc can have a corrosive effect on human skin and damage the nervous membrane. Therefore, it is very important to have a standard guideline to monitor the level of contaminants in water. A rapid and efficient system for contaminants detection at lower concentration levels can be useful. Table 1 lists the standard of contaminants in drinking water set by the World Health Organization (WHO).

Table 1
Contaminants standard in drinking water

Pollutants	WHO	EPA
Nitrate	0.05	-
Phosphate	5 ppm	-
Zinc	5 ppm	5 ppm
Copper	1.0 ppm	1 ppm
Arsenic	0.05 ppm	0.01 ppm
Lead	0.05 ppm	0.015 ppm

Many researches have proposed various methods to detect these contaminants above in water, such as spectrophotometric, chromatography (Kodamatani et al., 2009), potentiometry (Hassan, 1976), amperometric, and biosensor (Albanese et al., 2010). However, these methods have their own drawbacks such as exposure towards emission of hazardous gases, measurement error due to interference from other contaminant, kinetic charge transfer at electrode surface are low thus direct reduction of nitrate is characterized by poor sensitivity and reproducibility, low sample throughput and large scale equipment, lengthy analysis time, costly instrumentation requirements, as well as utilization of toxic regents and carrier solution, and limitation of large sample size required. Due to these issues, PESA is introduced to determine the near-to-the-surface properties, such as dielectrics, permeability and conductivity (Ong et al., 2001) (Hofmann et al., 2005). The applications of PESA can be found in food safety, sheep skin estimation, and bacterial content detection (Ong et al., 2001) (Yunus et al., 2009) (Hofmann et al., 2005), where the sensors are sensitive to the different magnetic susceptibilities and dielectric properties of each material (Nor et al., 2013) (Ong et al., 2001). Research (Yunus et al., 2015) proved that the coating layer could vary the sensitivity of the sensor. On the other hand, protective layer could protect the sensor surface from extreme chemical reaction from contaminants. This research focuses on developing PESA with different types of coating to detect nitrate, phosphate, zinc, and nickel.

PESA FOR NITRATE, PHOSPHATE, ZINC, AND NICKEL DETECTION

PESA Architecture and Detection Principle

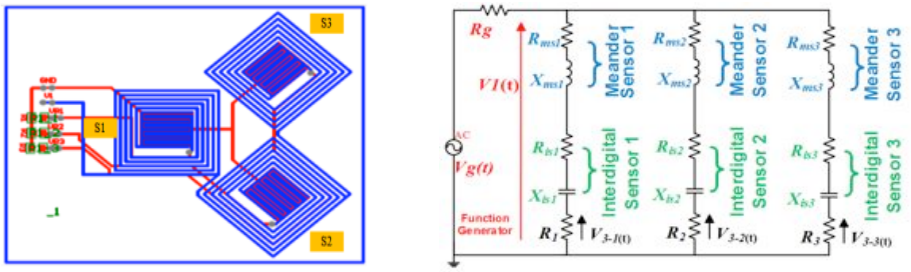
In this section, the architecture and detection principle of PESA for contaminants measurement are elaborated. PESA consists of a series-connected meander sensor and an interdigital sensor.

The sensor array is fabricated in a thin substrate such as a printed circuit board (PCB) using the conventional PCB fabrication technique. The meander sensor consists of several loops or coils of electrodes and is designed to be spiral or square shape. The interdigital sensor consists of positive and negative electrodes and is designed to be parallel between positive and negative electrode. The ground electrode is placed at the bottom of the interdigital sensor. The combination of the meander and interdigital type provides the best sensitivity. The architecture of the sensor array is illustrated in Figure 1.

(a) (b)

Figure 1. Planar electromagnetic sensor architecture (a) Top view (b) Bottom view

According to Figure 1, the sensors consist of a meander sensor and an interdigital sensor which are connected in series. The proposed dimension of meander sensor is 20 mm 20 mm. A meander sensor is built based on five loops of coils. The interdigital sensor is designed based on consecutive positive electrode and negative electrode. The proposed interdigital width for positive electrode and negative electrode are 0.5 mm and 1 mm respectively. In this research, planar electromagnetic sensor with star array configuration is used. Based on research in (Nor et al., 2013, 2015), star array configuration has the highest sensitivity. Figure 2 illustrates the star configuration and equivalent electrical circuit diagram.



(a) (b)

Figure 2. (a) star configuration; (b) equivalent electrical circuit diagram

Three sensors namely S_1, S_2 and S_3 are placed in a star array configuration. These three sensors are placed 10 mm apart. S_2, and S^3 which are placed 45° and - 45° respectively from S1. The schematic diagram of the meander sensor and interdigital sensor is shown in blue. The ground plane connection on the other side of the PCB is presented in red. In this research, the equivalent electrical circuit of the sensor is illustrated in Figure 2 (b). According to Figure 2 (b), the sensor is connected to a function generator where Rg is the output resistance with a nominal value of 50 Ω.R_1 denotes the series surface mount resistor connected to sensor 1 (S_1), as shown in Figure 2 (a). Therefore, current $I_{3\text{-}1}$ can be calculated from

$$I_{3-1} = \frac{V_{3-1}}{R_1} \tag{1}$$

where $I_{3\text{-}1}$ and $V_{3\text{-}1}$are the rms value of current through the sensor and voltage across R_1 respectively. The absolute total impedance for sensor S_1, Z_1 is given by

$$Z_1 = \frac{V_1}{I_{3-1}} \tag{2}$$

where V_1 is the rms value of the input voltage signal. Consider that θ_1 is the phase difference between V_1(t) with $V_{3\text{-}1}(t)$ in degree, taking $V_{3\text{-}1}(t)$ or $I_{3\text{-}1}$ as a reference. The total impedance of sensor S_1, Z_1, can be written as:

$$Z_1 = \frac{V_1 \angle \theta_1}{I_{3-1} \angle 0^\circ} \tag{3}$$

The same method of calculation can be used to calculate the impedance for both sensors S_2 and S_3 by using Equations (1) to (3).

EXPERIMENTAL SETUP AND ANALYSIS

The experimental setup is categorized into three parts; they are sensor, system, and sample. Firstly, the PESA with a star array configuration is fabricated. This sensor is then coated with membrane. A function generator supply AC source to PESA. Meanwhile, the oscilloscope is used for the data acquisition. LabVIEW software is used for data display and analysis. Figure 3 illustrates the experimental setup of the research. 10 Volts peak-to- peak voltages is supplied by means of function generator at each terminal sensor. Four channels oscilloscope that being link online with PC and a holder to hold the sensor which was immersed into a beaker and prepared samples. The oscilloscope is interfaced to a PC where the output signals and the sensor's impedance was recorded and calculated consecutively using LabVIEW software for a period of times. In this research, the frequency is set from 1 kHz to 20 MHz. In order to characterize the effect of coating on sensor performance, the whole procedure is repeated using PESA coated with Incralac. Four types of different samples were prepared. There are nitrate, phosphate, zinc, and nickel solution at different concentration level (5ppm, 25ppm, 75ppm, and 100ppm). The samples are subjected to PESA.

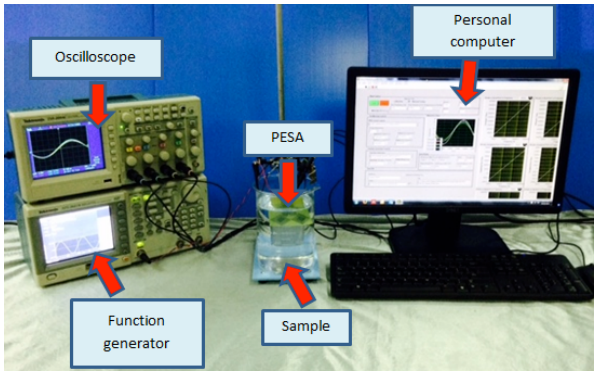
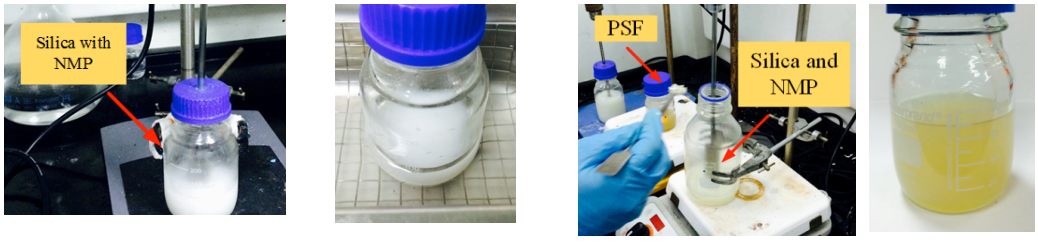


Figure 3. Experimental setup for nitrate, phosphate, zinc, and nickel samples

MEMBRANE POLYMER DOPE DEVELOPMENT PROCEDURE

All the reagents are analytical grade unless otherwise stated. Firstly, silica powder (10.1348 g) and N-Methyl-2-pyrrolidone (NMP) are mixed for 30 minutes using stirrer machine (IKA RW 20 digital) at the speed of 500 rotation per minute (rpm). This mixing process is demonstrated in Figure 4(a). Secondly, the mixture of silica and NMP were inserted into ultrasonic cleaner machine (3MX) for degassing process. This process takes 60 minutes to disperse the particles in the mixture. The illustration of degassing process is shown in Figure 4(b). Then, 25 g of poly-sulfone (PSF) is added into the mixture of silica and NMP. To ensure the mixture mixed thoroughly, the PSF is inserted gradually and stirred using IKA machine for 4 hours in 750 rpm as illustrated in Figure 4(c). Next, NMP (10 g) is added into the mixture and leave it for 24 hours. Lastly, the mixture is left in ultrasonic cleaner machine (3MX) for 3 hours for degassing process. Figure 4(d) demonstrates the membrane polymer dope which consists of silica, NMP and PSF.



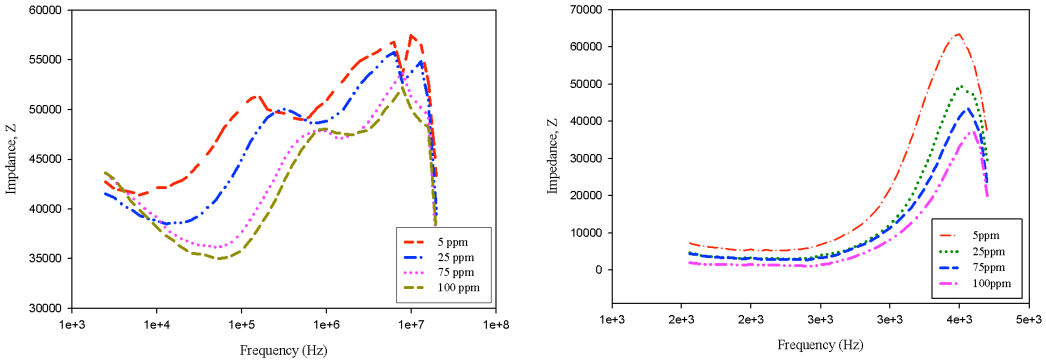
(a) (b) (c) (d)

Figure 4. Experimental setup for nitrate, phosphate, zinc, and nickel samples

The prepared membrane is then transferred into the beaker for the coating process. Robot arm is employed to hold the planar electromagnetic sensor and helps to immerse the sensor into the beaker for almost 10 seconds. Then, the sensor is pulled out slowly in order to get smooth coating surface. Finally, the coated sensor is inserted into the oven for 24 hours at 50°C.

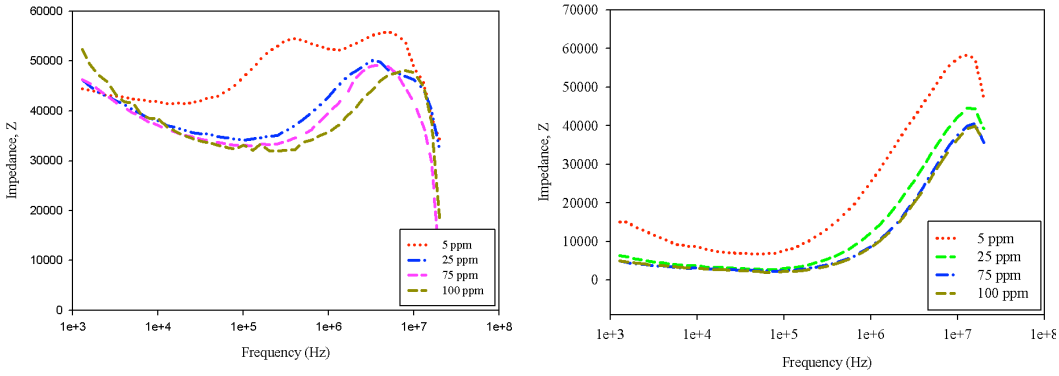
RESULT AND DISCUSSION

Figure 5 and Figure 6 depict the impedance, Z using PESA with a star configuration for different concentrations of nitrate and phosphate solution respectively. The graphs in Figure 5 and Figure 6 show the impedance for both sensor which are coated with membrane and Incralac. Based on the measured data, it can be seen that the total impedance responses vary with the different samples of nitrate and phosphate. Basically, for the star array sensor, the total impedance value decreases as the concentration of these contaminants solution increased from 5 ppm to 100



(a) (b)

Figure 5. Impedance for different concentration level of nitrate (a) coated with Incralac; (b) coated with membrane



(a) (b)

Figure 6. IImpedance for different concentration level of phosphate (a) coated with Incralac; (b) coated with membrane

ppm. Hence, it shows that the presence of contamination in water could increase the water conductivity. At the same time, the permittivity of the medium under test also increase with the increased in contamination level. The obtained data in this research agreed with the paper in (Nor et al., 2015; Wang et al., 2015).

Table 2
Absolute sensitivity, |Z%| for different concentration level of nitrate, phosphate, nickel, and zinc

Part per million (ppm)	Nitrate		Phosphate		Nickel		Zinc	
	Membrane	Incralac	Membrane	Incralac	Membrane	Incralac	Membrane	Incralac
5	14-99	47-55	20-28	8-56	2-331	1-52	77-224	0.27-71
25	26-99	42-64	13-98	12-61	0-338	0.5-45	93-192	2-60
75	35-100	38-60	35-99	6-65	1-92	2.7-55	12-94	0.02-69
100	42-100	34-60	36-99	6-62	1.8-93	0.55-62	93-204	1-71

Table 2 summarized the absolute average impedance sensitivities, |Z%| for nitrate, phosphate, zinc, and nickel. Sensitivity is calculated based on the equation in (Yunus et al., 2015). Based on the result, PESA with star configuration could distinctly differentiate or give a vary response for different concentration of nitrate, phosphate, zinc, and nickel. PESA coated with membrane shows higher sensitivity compared to Incralac for all measured samples. The highest sensitivity is 338 % which observed in the presence of membrane for the nickel detection. In the meanwhile, the lowest sensitivity using membrane is 12 % for zinc detection. However, for Incralac coating, the highest sensitivity is 71 % and the lowest sensitivity is 0.02 %. The absolute impedance sensitivity value has increased approximate two times higher than the sensor coated with Incralac. The absorption of the nitrate ion on the membrane has changed the nature of the output (impedance). Hence, makes the PESA to be more sensitive to all measured samples.

CONCLUSION

The membrane and Incralac coaters have been successfully coated on the PESA surfaces. The results demonstrate that the PESA could give different responses for different contaminant concentrations values in different ranges of frequencies. The result indicates that PESA coated with membrane has the highest sensitivity. In the future, an artificial neural network (ANN) classification method will be employed to increase the validity and to estimate the level of contamination of water samples taken from natural sources, such as rivers or lakes.

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