

A Fractional Order Impedance Sensor for Measuring the Quality of Drinking Water

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Abstract—A new stick type sensor is fabricated to analyze the quality of drinking water. The sensor has fractional order impedance, which shows constant phase behavior over a wide frequency range (200 kHz to 1 MHz) in drinking water. The parameters of the sensor, such as the constant phase angle (θ) and the fractional exponent ($\alpha \leq 1$) vary with the change in the ionic impurities of water. Fabrication of the sensor is easy, requires cheap materials, and is bulk producible at low cost. For 600 ppm change in the total dissolved solids value of the water sample, there is nearly an 18° shift in the phase angle of the fabricated sensor. The sensor can be utilized to make a prototype probe. A preliminary experimental work is carried out to explore the effectiveness of the sensor to measure the quality of drinking water.

Keywords- Sensors; fractional order; impedance; drinking water; quality monitoring.

I. INTRODUCTION

Water is mankind's most precious resource and one of the necessities for the existence of all living beings. Unfortunately, it is often contaminated with various impurities, such as organic, inorganic solvents and microorganisms [1][2]. Disposal of industrial, pharmaceutical and other waste materials to different water resources causes water contamination [2][5]. The most common drug contaminant found in the fresh water is the non-steroidal anti-inflammatory drug ibuprofen. Similarly, the teratogenic and the carcinogenic effects of the phthalate esters, which are used to manufacture different plastic food packages and the other plastic containers pose great danger to all living beings and to the environment [5]. Other common sources of water contamination are the use of nitrate and phosphate salts for agriculture [6][7]. In many developing countries, the contaminated drinking water is a major concern for the human health. Due to inadequate supply of the pure drinking water, people sometimes are compelled to consume untreated ground water or to purchase costly commercially available packaged (plastic container) mineral water [2][5]. Because of high price, sometimes, local vendors add untreated low-cost water to costly mineral water for earning more money. Water impurities can be defined based on the dissolved solids and microorganisms present in the water. A high amount of the

dissolved solids can indicate poor water quality, which is harmful for health.

The conventional methods of impurities measurement require separation of the impurities using liquid or gas chromatography technique and subsequently, the mass measurement using a mass spectrometer. The recent technique called electronic tongue is reported for water quality analysis by the authors [8]. The arrays of the sensors in electronic tongue may be of different types, such as surface acoustic wave, conductive polymers, metal oxides, Chem FET, optical, electrochemical, etc. These methods are accurate and reliable but are costly, require skilled man power for their operation, have long analysis time and are not portable for the field testing. Due to the constraints associated with these techniques, the routine analysis of the water samples is normally avoided.

Important parameters for water quality monitoring are pH value, chlorine concentration, flowrate, temperature, turbidity, conductivity etc. A review article on current technologies and future needs of water quality analysis is reported in [9]. Some other reported techniques employ multi sensors fusion data analysis using Dempster-Shafer evidence theory [10] or optical method for bacterial growth monitoring [11]. Some simple methods are present to measure the Total Dissolved Solids (TDS) like the gravimetric method, and the electrical conductivity method [1]. TDS meter is based on the second method, where one can measure the TDS value by dipping the probe into the water sample. Sometimes, a capacitive sensor is used to determine the electrical parameters of water [12] but the sensor has complex design and requires necessary precautions to measure the small capacitance value in presence of unwanted parasitic earth capacitance. According to the world health organization (WHO), the TDS value of the drinking water below 600 ppm is safe for consumption. Therefore, there is a need to develop a quick, low cost and user-friendly probe to measure the ionic impurities of the water sample [1].

This paper presents a constant phase (CP) fractional order sensor to analyze the quality of commercial mineral water available in the market. A fractional order device is identified by two important parameters, (i) the fractional order α , and (ii) the constant phase angle over a certain

range of excitation signal frequency. There are several real-world phenomena which show fractional order behavior. An infinite ladder network or a domino network shows the constant phase behavior over a certain frequency range at the fractional order value of nearly 0.5 [13]. The constant behavior is also observed by a conductivity sensor as reported in [14] but rarely any constant phase sensor is available in the market. A constant phase element can also be fabricated by making fractal structure on silicon substrate at $\alpha = 0.46-0.5$ [15].

In this work, we have studied the response of a fractional order (α) impedance sensor fabricated with double sided copper cladded printed circuit board substrate to measure the ionic impurities of mineral water. Due to the change in ionic impurities, the phase angle and the fractional exponent of the sensor will change. The order and the phase angle vary within 0-1 and 0-90° respectively. Thus, motivation behind this work is to develop a fractional order probe to measure the quality of commercial packaged drinking water. The proposed sensor is easy to fabricate, requires cheap materials for fabrication and is bulk producible at low cost. A preliminary experimental result with some commercial packaged mineral water samples are reported. Theory of the sensor is discussed in section II. In section III, detailed experiments including the sensor fabrication, experimental methods and results are given. Discussion about the experimental results is given in section IV. In section V, the conclusion about the research work is discussed.

II. THEORETICAL ASPECTS

The impedance of a fractional sensor in Laplace form can be expressed by the expression [13], $Z(S) = QS^{-\alpha} = Q(j\omega)^{-\alpha} = \frac{Q}{\omega^\alpha} \angle \left(-\frac{\pi}{2} \alpha \right)$ where, S (= j ω) is the Laplace operator, ω is given by $(2\pi f)$, with f is the signal frequency, and α is the order of the element. The magnitude (= Q/ω^α) depends on the frequency, and the fractional exponent α . But the phase angle $\theta = \left(-\frac{\pi}{2} \alpha \right)$ depends on the value of the fractional exponent only.

Thus, a fractional order sensor is identified by the value of fractional exponent and the constant phase angle over a certain frequency range. The value of the fractional exponent varies from -1 to +1. An ideal capacitor, an ideal resistor and an ideal inductor behave as the constant phase device for $\alpha = 1$, $\alpha = 0$, and $\alpha = -1$ respectively. These fractional devices in recent times are found some interesting applications in measurement systems and circuits [14]–[16]. For sensing applications, the characteristics of the constant phase impedance (CPI) in presence of the ionic impurities are mainly functions of three parameters as given by [16] $\theta = f(A, t, \sigma)$,

where, σ represents the ionic concentration of the medium under test, A is the area of contact of the probe with the test medium and t is the thickness of insulation film on the electrodes. However, the porous rough surface of the insulating film plays an important role for the CP behaviour. The measurement of the response is based on the change in phase angle and the fractional order of the CPI due to the change in ionic property of water. Due to the variation of ionic impurities, the parameters of the CPI will change, which in turn helps us to analyze the quality of water.

III. EXPERIMENTS

A. Preparation of the Polymer Insulation Solution

Insulating layer for the fabrication of the CPI is the film of polymethayl metha acrylate (PMMA). 5 % PMMA solution was prepared using PMMA flex and chloroform [16]. Nearly, 5 gm PMMA flex was added in 95 ml chloroform, and then, the solution was stirred on a magnetic hot plate stirrer at 50°C temperature for 2 hrs. Finally, the solution was de-aired to remove the bubbles formed during the stirring process.

B. Fabrication of the CPI Sensor with Double side Copper Cladded PCB Substrate

Fabrication of the sensor requires double or single sided metal coated (copper cladded) printed circuit boards (PCB). These boards are normally used to solder the discrete components of a circuit. The circuit board may be of the copper cladded epoxy resin glass or the copper cladded polyimide substrate, on which a thin porous insulating film was deposited. The porous insulating film may be made of polymer or metal oxide material. While selecting an insulating film, care must be taken to ensure the stability of the insulating film. Desirable characteristics of the fabricated sensor depend on (1) electrode geometries (2) crack free film (3) thickness of the film (4) film uniformity and the morphology of the porous film. Copper cladded polyimide (Upilex, Japan) was used for the CPI fabrication. Polyimide materials are lightweight, flexible, resistant to heat and chemicals and the cost is cheap for the bulk production. A polyimide substrate with double side copper cladded film of size 4 cm × 1 cm was cleaned in dilute sulphuric acid solution (H₂SO₄) for 5 min. The substrate was then dipped into the PMMA solution vertically with the dip in length 20 cm for nearly 30 s.



Figure 1. PMMA coated CPI sensor on polyimide PCB substrate.

An automatic dip coater was used to deposit the PMMA film of nearly 250 μm thickness on both sides of the substrate. The substrate was then dried in air at normal atmospheric condition for 24 hrs. Two copper wires were soldered at the electrodes for the electrical connection. Fig. 1 shows the photo of the PMMA based double sided CPI sensor.

B. Fabrication of the IDT Electrode CPI Sensor

For the fabrication of the IDT electrode CPI, the schematic diagram of the sensor is shown in Fig. 2(a). The IDT structure with the dimension shown in the diagram was designed using Autocad software. A screen of the design was prepared. The design was then printed manually on the single side copper cladded polyimide substrate. The substrate with the IDT electrode structure was dipped into the copper etching solution (Ferric chloride) for nearly ~ 10 min to remove the copper layer from the unmasked area. The substrate was then cleaned in DI water and in acetone. Finally, the substrate with the IDT electrode was dipped into

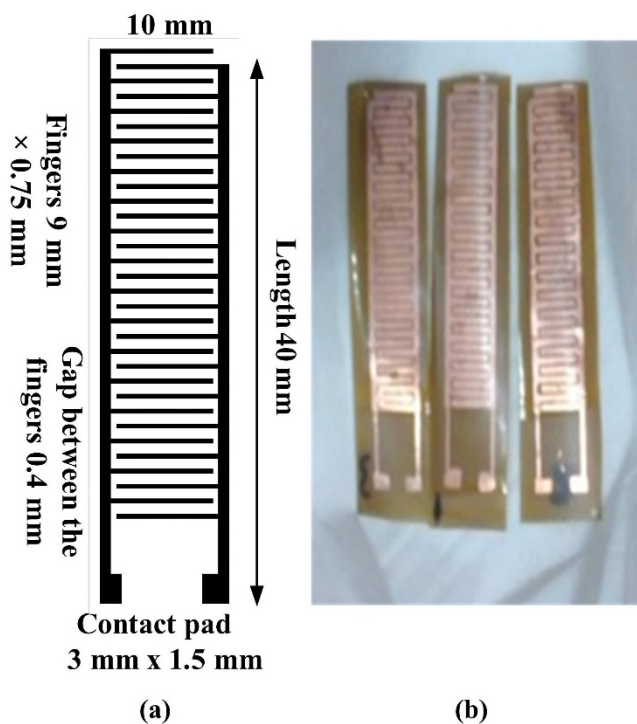


Figure 2. IDT electrode PMMA coated CPI sensor (a) schematic diagram, (b) photo of the sensors.

the PMMA solution for nearly 30s to deposit the insulating thin film of the PMMA. Fig. 2(b) shows the photo of the IDT sensor. Three IDT structured CPI sensors with different insulation thickness were fabricated to optimize the performances of the sensors. The insulating film deposited on the electrode is having large number of voids of ~ μm dimension resulting high effective surface area

[16][17]. The FESEM image of the insulating film is shown in Fig. 3. The IDT sensor with single PMMA coating provided better performance and was tested for analyzing the quality of water.

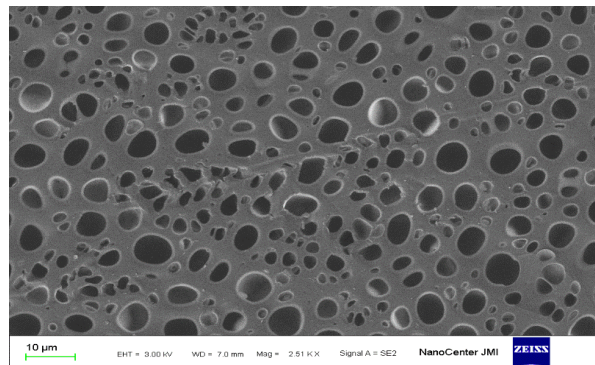


Figure 3. FESEM image of the PMMA insulating film deposited on the electrode.

C. Testing of the Sensors with Different Water Samples

Impedance analyzer (LCR meter) was used for testing the fabricated sensors. Parameters like impedance, and phase angle of the sensor in Z-θ mode were measured by the instrument. Each sensor was excited by the sinusoidal AC voltage signal of 1 V (rms) and the frequency was varied in the range of 5 kHz to 5 MHz. For determining the parameters of the CPI, mineral water samples from local market around the University campus, (New Delhi, India) were collected. Initially, the TDS value of each water sample was measured by the commercial TDS meter (accuracy ± 5%). We used the commercially available TDS meter as a reference meter to measure ionic impurities present in the water samples. TDS meter works on conductivity measurement principle. With increase in ionic impurities, the conductivity increases, hence, the TDS value of the water sample increases.

The TDS value of the water samples is shown in Table I. All the water samples are having TDS values, which are within the limit suggested by WHO. Deionized water (DI) which was almost ions free prepared using Millipore water purifying system was also used for testing the sensors (TDS = 0 ppm). Each water sample of 80 ml was taken in a cleaned glass beaker of 100 ml. The sensor was dipped into the beaker at a dip in length of 1 cm. Since, the behavior of the CPI depends on three parameters, so one parameter is the variable that is the ionic concentration of the medium and the other two parameters such as the contact area with the medium and the thickness of insulating film were kept constant. Temperature of the water samples was maintained at 25°C. The readings of the LCR meter in Z-θ mode were acquired into the computer. Each experiment for a water sample of fixed volume was repeated at least for five times to ensure the repeatability of the

reading. Average values of five readings were plotted. The maximum standard deviation of the readings of the phase angle value was approximately 0.48. Small deviation from the average value was due to minor variation of the dip in length of the sensor, since the phase angle of the sensor also depends on the contact area. Fig. 4 shows the variation of the phase angle of the sensor. For a certain frequency range, the sensor shows the constant phase behavior. The phase angle of the sensor for different water samples varies with the variation of the signal frequency, but it is almost constant phase over a wide frequency above 200 kHz. There is nearly a 10° shift in the phase angle of the sample 5 from the sample 1, a commercial popular brand (Bisleri). Bisleri is one of the most popular mineral water brands in Delhi. We also performed experiments to determine the response of the sensor with the mineral water sample 1 adulterated by adding impure water having more TDS value. Bisleri was assumed to be a pure reference water and untreated ground water having high TDS value was taken as the impure water.

TABLE I: TDS VALUE OF DIFFERENT WATER SAMPLES

Water Samples	TDS value (ppm)
DI Water	0
Sample 1 (commercial bisleri)	120
Sample 2	250
Sample 3	295
Sample 4	340
Sample 5	600

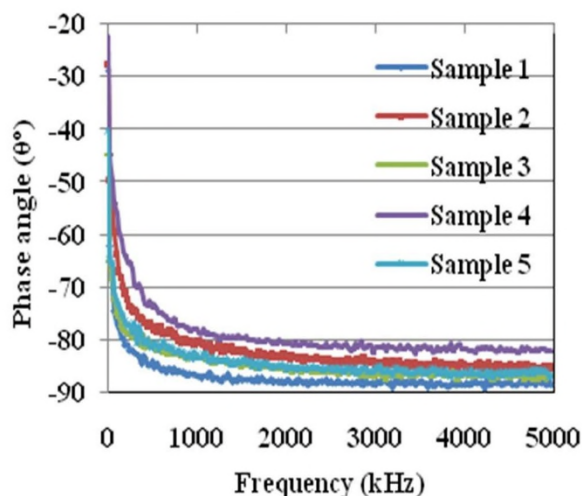


Figure 4. Change in phase angle of the sensor with frequency of different water samples.

The change in phase angle of the sensor for different adulterated water samples with the variation of the frequency is shown in Fig. 5. Again, the CPI sensor shows well defined constant phase behavior above 200 kHz for the adulterated and the

pure water but the shift in phase angle of the adulterated sample is very significant. For 20% adulteration of the Bisleri water, there is nearly 20° shift in the phase angle (at $f = 400$ kHz).

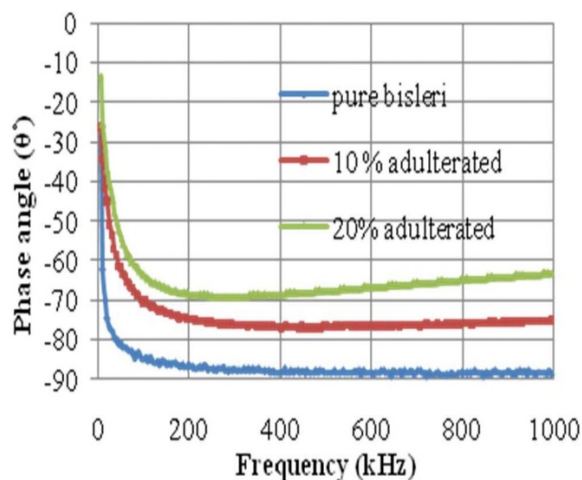


Figure 5. Change in phase angle of the sensor with frequency for the adulterated water samples.

Experiments were then performed with the IDT CPI sensor. Variation of the phase angle with the variation of the signal frequency in the range of 5 kHz-1 MHz is shown in Fig. 6. The IDT sensor also shows the constant phase response over a certain frequency range. However, the sensor in Fig. 1 shows much better constant phase behaviour than the IDT sensor shown in Fig. 2.

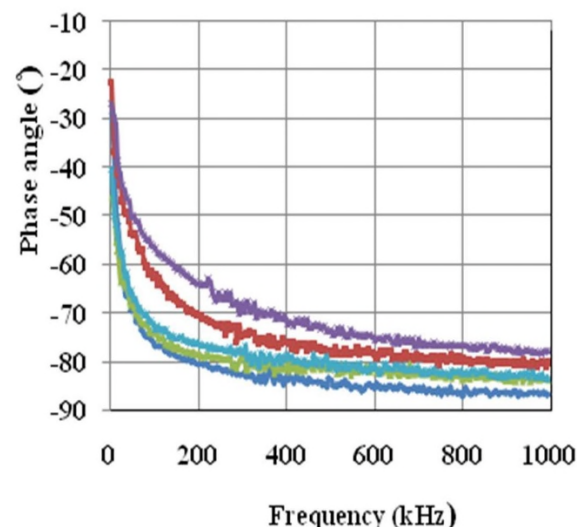


Figure 6. Variation of the phase angle with frequency of the IDT sensor for different pure water samples.

IV. RESULTS AND DISCUSSIONS

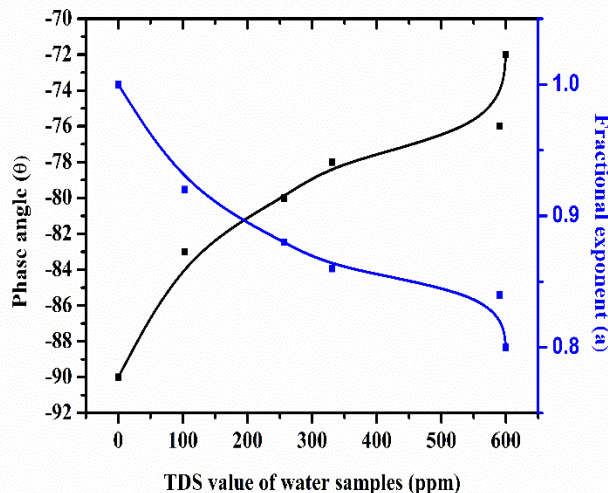


Figure 7. Variation of the phase angle and the fractional exponent with TDS value of the sensor.

The CPI sensor is identified by the constant phase behavior, and the fractional exponent (α), which are independent of the frequency. The parameter α can be determined using the expression $\alpha = -2\theta/\pi$, where θ is the phase angle of the sensor. Using this expression, the values of α were determined at different frequency.

Fig. 7 shows the variation of the phase angle and the fractional exponent of the CPI sensor with the variation of TDS value of the drinking water samples at 400 kHz signal frequency. With increase in TDS value, the conductivity of water increases, hence, the values of the phase angle and the fractional exponent decrease. Therefore, the sensor shows a correlation between the TDS value and the parameters of the CPI sensor.

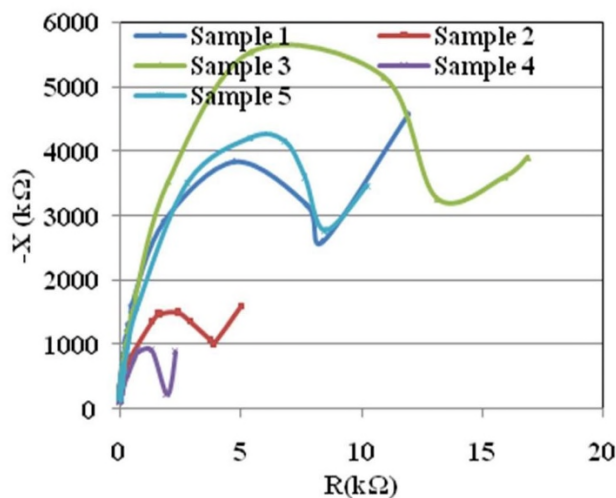


Figure 8. Complex impedance plot of the sensor for different water samples.

Experiments were also performed with DI water (Grade II) having resistivity of 14 MΩ.cm. DI water is almost free from ions, therefore, the sensor is having fractional exponent value close to 1 ($\alpha = 1$ for perfect capacitor).

The complex impedance data showing the negative of imaginary component of the impedance (Z) is plotted with the real component of the impedance with the variation of the signal frequency. The plot is shown in Fig. 8.

Data of the impedance was obtained from the actual experiments with different water samples in $Z-\theta$ mode of the Impedance analyzer over a frequency range of 5 kHz to 5 MHz. Each of the responses has two distinct parts namely (i) a semicircular part and (ii) a curved straight line. Both the parts vary with the variation of the water types. Semicircular response at higher frequency can be represented by the parallel combination of the resistance and the capacitance. The radius of the semicircle reduces with increase in conductivity of the water samples. The curved straight line towards the lower frequency indicates the diffusion of ions through the macro pores of the insulating film on the electrode [16]. Insulating film of PMMA has macro porous structure as shown in the FESEM image of Fig. 3. Pores are of different size but of the order of micrometer (μm). When the sensor is dip into water, the water molecules contact the electrode through these macro pores. In presence of water, each pore can be represented by an RC network. Values of the equivalent resistance and capacitance of the network depend on the conductivity as well as dielectric constant of the water. Inhomogeneous macrostructure of the insulation and the presence of large number of voids, cause formation of a distributed RC network with different (RC) time constants. Such distribution of the time constant gives the constant phase behavior of the sensor [13], [16]-[17]. For a prototype meter, this change in phase shift of the sensor can be converted into a voltage signal using a phase detection electronic circuit.

V. CONCLUSION

This paper presented the initial study of the constant phase sensors and their application for analyzing the quality of drinking water. Fabrication of the sensors is very easy and is bulk producible at low cost. The sensors were tested with pure and the adulterated mineral water samples. The sensors showed the constant phase behavior over a wide frequency range. But the CP and the fractional exponent varied with the variation of the ionic impurities. The phase angle at a particular excitation frequency can be converted into a voltage signal using an interface circuit. The output of the interface can be calibrated to make a stick type probe for the vendors and household application. Initial results showed that the sensor may be suitable to make a ball pen type probe for testing drinking water including its adulteration with impure water. However, detailed investigation with large number of water samples

from different commercial brands and different CPI sensors with different pore morphology with more stable insulating films are needed to establish the effectiveness of the sensors for water quality monitoring.

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