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Determination of Sugar Content in Sugar Solutions using Interdigital Capacitor Sensor

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A novel low-cost electronic tongue system for sugar content determination in sugar solutions is proposed. The system consists of a sine wave generator, a resistor, and an interdigital capacitor sensor forming a first-order electronic high-pass filter circuit. The interdigital capacitor sensor has the planar interdigital structure and the consecutive fingers are connected to positive and negative electrodes. The system has been assembled and the experiments were conducted. The experimental results show that the proposed system has a great potential to determine the sugar content in sugar solutions. It also provides an opportunity for the development of a microcontroller-based low-cost sensing system as an electronic tongue system.

Keywords: Interdigital capacitor, high-pass filter, relative permittivity, electronic tongue, sugar concentration

1. INTRODUCTION

IN FOOD INDUSTRY there is a need for objective high-throughput taste profiling to complement sensory panels. Sensory and instrumental techniques are traditionally used to determine the taste of food products. Consumer panels give by far the most realistic image of the taste of a product as experienced by humans. Sensory analysis, however, has some drawbacks, such as the correctness of training, standardization of measurements, reproducibility, high cost and taste saturation of the panelist [1]. Spectroscopy, gas chromatography (GC), high-pressure liquid chromatography (HPLC), and other instrumental techniques determine the chemical composition of a food product and can be used to describe the taste of product. These traditional techniques have some drawbacks. They require laborious and time-consuming sample preparation. Moreover, skilled people are needed to operate the equipment.

“Electronic tongues” have shown to be a good candidate for spectroscopy and traditional chromatographic techniques in the food analysis. Different tasks such as quality evaluation and control, discrimination and classification, process monitoring, and quantitative analysis for food products have been successfully performed with electronic tongues [2]-[8].

The development of sensing devices for fast and reliable monitoring of sugar or sweetness in solutions is very important in food and juice industries, and in wine manufacturing. The low-cost, real-time, and easy-to-handle measurement setup is strongly required in the electronic tongue system for food and juice industries, and in wine manufacturing.

For measurement technologies, relative permittivity changes or capacitive changes are used as a factor for monitoring the environments and for measuring the material properties [9]-[12].

Among sensor technologies [13]-[18], interdigital capacitors are used for the evaluation of near-surface properties, such as conductivity, permeability, and permittivity of materials [19]-[22]. The interdigital sensors have been used for estimation of properties of dielectric material for dairy products [23], humidity and gas sensors [24], biosensor applications [25]-[28], and detection of dangerous toxins in contaminated seafood [29]. The applications of these sensors depend on both the characteristic of the particular sensor chosen and also on the characteristic of the material under test (MUT). Therefore, there is a possibility to develop the interdigital capacitor for a novel low-cost sensing system in food and juice industries.

In this paper, a first-order electronic high-pass filter circuit with interdigital capacitor sensor is proposed as a novel low-cost electronic tongue system for sugar content determination in sugar solution. It seems to be a promising technique for food and juice industries.

This paper is organized as follows. In section 2, the first-order electronic high-pass filter circuit and the basic interdigital capacitor sensor are discussed. In section 3, the electromagnetic properties of sugar and water are described. The details of the experimental setup and measurement procedure are described, and the experimental results are presented and discussed in section 4 followed by the conclusion in section 5.

2. FIRST-ORDER HIGH-PASS FILTER CIRCUIT AND INTERDIGITAL CAPACITOR SENSOR DESIGN

In this section, a first-order high-pass filter circuit and an interdigital capacitor are designed for the proposed electronic tongue system.

The first-order high-pass filter consists of an AC source (V_{ac}), a resistor (R), and a capacitor (C) as shown in Fig.1. The transfer function of the filter circuit ($H(f)$) is calculated as follows [30]:

$$H(f) = \frac{V_0}{V_{ac}} = \frac{R}{R + \frac{1}{j2\pi fC}} \tag{1}$$

$$\left|H(f)\right| = \frac{R}{\sqrt{R^2 + \dfrac{1}{(2\pi fC)^2}}} \tag{2}$$

$$f_c = \frac{1}{2\pi RC} \tag{3}$$

where V_o is the output voltage, V_{ac} is the driving signal voltage, f is the operating frequency, and f_c is the cutoff frequency.

The transfer function of the circuit is illustrated in Fig.2 when R=5 $k\Omega$, and C=8.0248 pF are assumed. Then the cutoff frequency is 4 MHz.

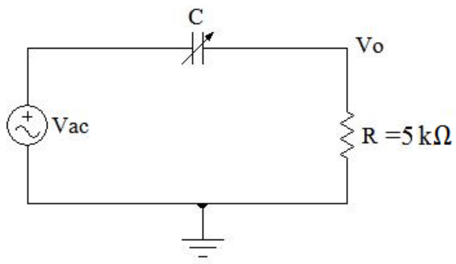


Fig.1. A first-order high-pass filter circuit.

In Fig.2, the transfer function characteristic illustrates that the slope is linear in the transition zone while other frequencies, which are higher than f_c, become saturated. The sensor capacitance can be changed due to the variations of sugar concentration. This can significantly change the linear slope in the transition zone and the cutoff frequency. Therefore, it is very suitable to utilize the transition zone for sugar content determination in sugar solutions.

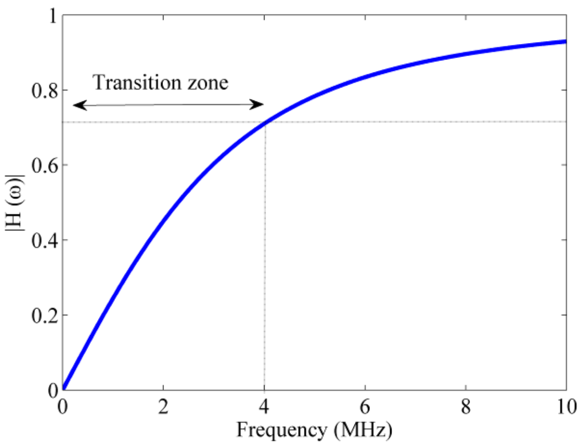


Fig.2. The transfer function of the first-order high-pass filter with R=5 $k\Omega$ and C=8.0248 pF.

The interdigital capacitor is chosen as the sensor for our system. The interdigital capacitor sensor has the same principle of operation as the parallel plate or coaxial cylinder permittivity sensor [31]. The voltage is applied to the interdigital capacitor electrodes, and the impedance across the capacitor electrodes is changed due to the frequency and capacitance variations. However, unlike the parallel plate capacitor, the interdigital capacitor sensor does not require two-sided access to the MUT.

The interdigital capacitor sensor in Fig.3 is specially designed on a printed circuit board (PCB) to transform the permittivity differences of sugar concentration into capacitance variations. The capacitance of interdigital capacitor sensor in Fig.3 is determined by summing the two-dimensional unit cell capacitance C_{UC} in Fig.3(b). The total capacitance of the interdigital capacitor is as follows [32]:

$$C = C_{UC}(N-1)L \tag{4}$$

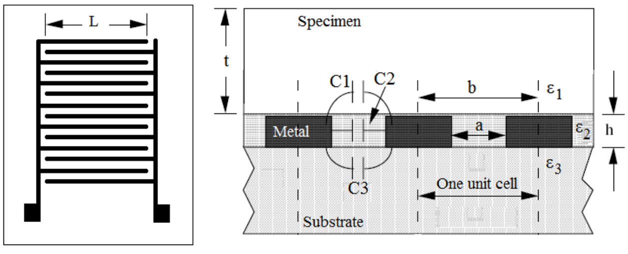
$$C_{UC} = C_1 + C_2 + C_3 \tag{5}$$

$$C_1 + C_3 = \varepsilon_0\left(\frac{\varepsilon_1+\varepsilon_3}{2}\right)\frac{K(\sqrt{1-k^2})}{K(k)} \tag{6}$$

$$C_2 = \varepsilon_0\varepsilon_2\frac{h}{a} \tag{7}$$

$$k = \frac{a}{b} \tag{8}$$

where N is the number of unit cells, L is the length of the electrode, ε_0 is the free space permittivity (8.854x10^{-12} F/m), ε_1 is the relative permittivity of the MUT, ε_2 is the relative permittivity of material between electrodes, and ε_3 is the relative permittivity of the PCB substrate. $K[x]$ is a complete elliptic integral of the first kind.



(a) (b)

Fig.3. (a) Top view of an interdigital capacitor. (b) Cross section view of the interdigital capacitor [32].

To design an interdigital capacitor for our paper, the dimension values of the sensor were: h=35 μm, t=5 cm, a=1 mm, b= 2 mm, L=20 mm, and N=20. The free space permittivity $\varepsilon_1 = \varepsilon_2 = 1.0$, and the relative permittivity of substrate (AD260A) ε_3=2.60. The total capacitance calculated from (4)-(8) is 8.0248 pF.

The proposed system for sugar content determination in sugar solutions consists of a first-order high-pass filter circuit with an interdigital capacitor sensor. The transfer function of the high-pass filter circuit is illustrated by the linear slope in the transition zone. Moreover, the interdigital capacitor sensor can sense the permittivity changes in the sugar solutions. This effect can change the cutoff frequencies and the linear slopes according to the capacitance changes in sugar solutions. Therefore, there is a possibility to use the proposed system for sugar content determination in sugar solutions by measuring the output voltage variations of the filter circuit.

3. ELECTROMAGNETIC PROPERTIES OF WATER AND SUGAR

The components in sugar solutions are water and sugar. Both materials have their own relative permittivity. Material model of distilled water was recognized by Debye in 1926 and describes the relative permittivity of water as a function of frequencies in (9) [33].

$$\varepsilon_{water} = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j2\pi f\tau} \tag{9}$$

where ε_∞ is the relative permittivity at the optical frequencies, ε_s is the relative permittivity at the static frequency, τ is electrical relaxation time, and f is the frequency. The values of these parameters for water are: ε_∞=4.60, ε_s=78.3, and τ=8.07 ps while the relative permittivity of sugar, considered to be a constant value, is $\varepsilon_{sugar} = 3.525 - j0.0025$ obtained from [34]. The relative permittivity of water is plotted in Fig.4.

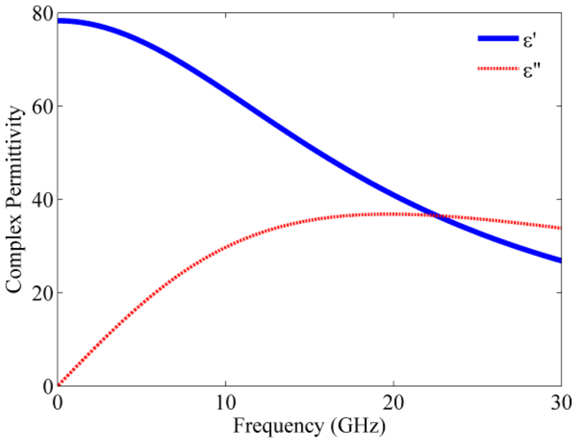


Fig.4. the relative permittivity of water with the Debye model.

For very low frequency such as the frequency of 200 kHz, the relative permittivity of water is $78.3 - j0.0007$. Since the imaginary parts of permittivity of water and sugar are very low, the capacitor loss can be neglected. The resistor R in the circuit is equal to $5\,k\Omega$. The upper limit of V_o can be calculated using (1)-(8) with the relative permittivity of water while the lower limit of V_o can be calculated using (1)-(8) with the relative permittivity of sugar. The V_o of both sugar and water are shown in Fig.5 when V_{ac} is equal to $10\,V_{peak}$. The V_o obtained from different sugar contents in the solutions should fall within the range. The voltage differences of V_o between water and sugar are shown in Fig.6. The maximum voltage difference occurs at the frequency of 300 kHz.

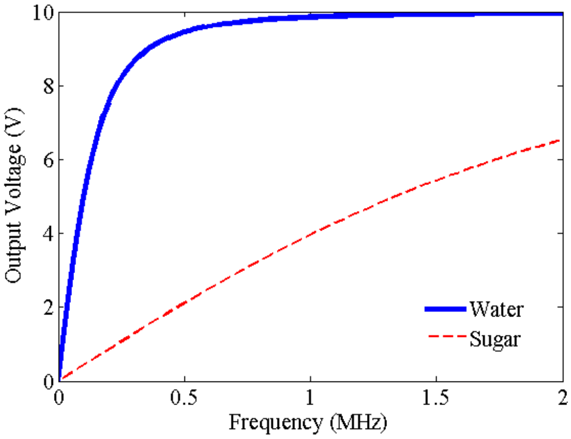


Fig.5. The output voltage calculated across the resistor are shown when the sensor is immersed into the water and the sugar.

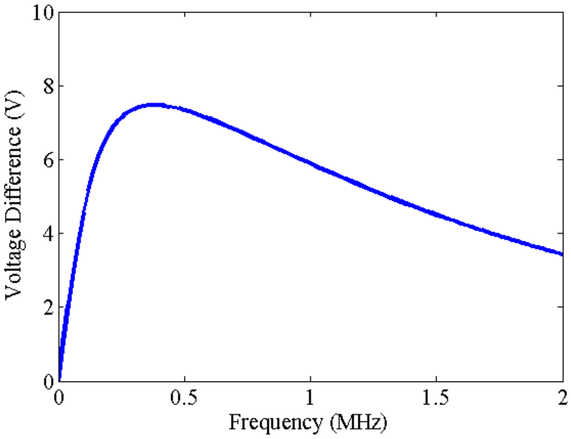


Fig.6. The output voltage difference between water and sugar with frequency variation.

4. EXPERIMENTAL RESULTS

The interdigital capacitor sensor is fabricated using the materials and dimension values from section 2. The interdigital capacitor sensor is connected to a resistor to form the first-order high-pass filter circuit. The total capacitance calculated is 8.0248 pF, and the resistance of R is $5\,k\Omega$. The fabricated sensor is illustrated in Fig.7, and Fig.8.

The first-order high-pass filter circuit with the designed interdigital sensor and the resistor is driven by a 10 V_{peak} sine wave source. The circuit is assembled from the schematic diagram in Fig.1. The experimental setup is illustrated in Fig.9. The interdigital capacitor sensor is immersed in a beaker containing a sugar solution. The driving signal for the circuit is provided by the GW Instek GFG-8217A function generator. The LeCroy LT354 digital oscilloscope is used for output voltage measurements.

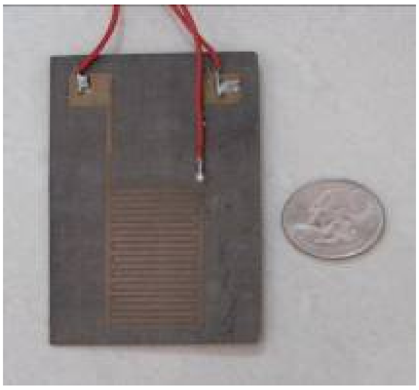


Fig.7. The front view of the fabricated capacitor sensor.

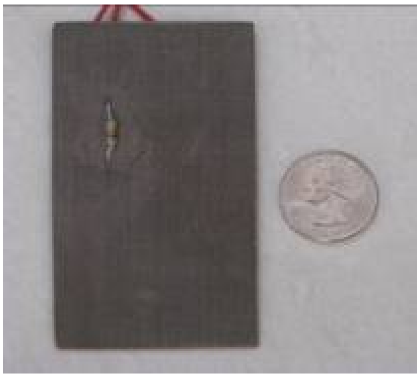


Fig.8. The back view of the fabricated interdigital capacitor sensor. It shows a resistor of 5 $k\Omega$.

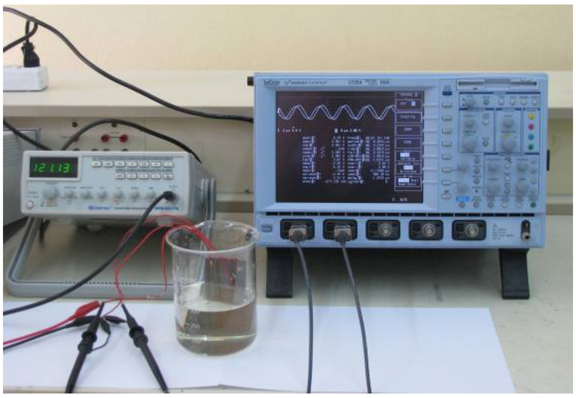


Fig.9. Experimental setup for sugar content determination in a sugar solution.

To verify our designed sensor, the initial investigation of the sensor is performed in air. The results are shown in Fig.10. In Fig.10, the measured and calculated results are in good agreement.

To determine the sugar content in sugar solution, the circuit is tested on different sugar solutions. The sugar solutions are prepared by mixing water and sugar. Different sugar solutions are prepared containing 10, 15, 20, 25, 30, 35, 40, 45, and 50 % sugar concentration by weight. The interdigital capacitor sensor is immersed into different sugar solutions in beakers. The circuit is driven by the 10 V_{peak} sine wave using the GW Instek GFG-8217A function generator. The driving signal frequencies are varied between 100 kHz and 800 kHz. The V_o are recorded using the LeCroy LT354 digital oscilloscope. Measured output voltages of different sugar solutions are plotted in Fig.11. The experimental results show that the output voltages of the solutions are decreased as the sugar concentrations in the solutions are increased.

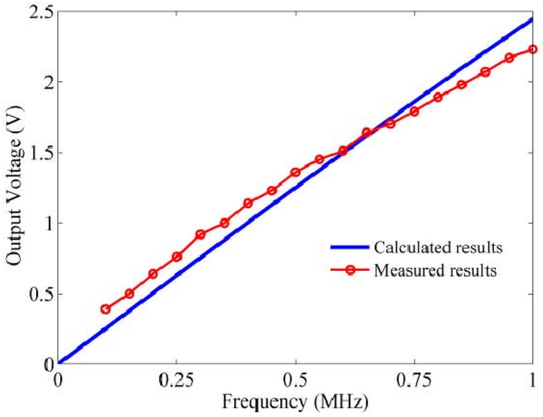


Fig.10. Comparison of calculated results and measured results of V_o is shown when the sensor investigation is performed in air.

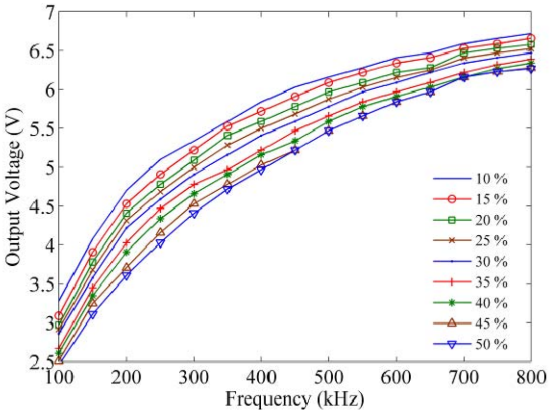


Fig.11. Output voltages of the resistor with different sugar solutions are plotted as a function of frequencies.

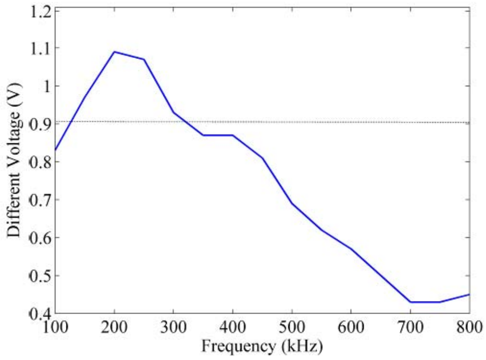


Fig.12. the output voltage differences between 10% and 50% sugar concentrations for different operating frequencies.

The output voltage differences between 10 % and 50 % sugar content in the solutions are shown in Fig.12 with different operating frequencies. The maximum output voltage difference between 10 % and 50 % sugar concentrations is 1.1 V, and occurred at the operating frequency of 200 kHz. Compared to other frequencies, the frequency of 200 kHz is the appropriate frequency to be implemented for the electronic tongue system because this frequency can provide the maximum output voltage difference when the sensor is tested with different sugar contents.

Nine sugar solutions were tested for sugar content determination. The output voltages across the resistor were measured with the operating frequencies between 100 kHz and 800 kHz.

All measured output voltages in Fig.11 fall within the range of the lower limits (from sugar) and the upper limits (from water) in Fig.5.

The maximum output voltage difference between 10 % and 50 % sugar concentration occurred at the operating frequency of 200 kHz as shown in Fig.12 while the maximum output voltage difference between sugar and water occurred at the operating frequency of 300 kHz as shown in Fig. 6. The curve of output voltage difference between 10 % and 50 % sugar concentration in Fig. 12 is similar to that of output voltage difference between sugar and water in Fig.6.

The output voltage differences shown in Fig.12 indicate that the measurement at the frequency range of 120-300 kHz provides the opportunity for the development of a low-cost electronic tongue associated with any microcontroller system.

5. CONCLUSION

This paper has reported a novel low-cost electronic tongue system for sugar content determination in sugar solutions. The system utilizes a first-order electronic high-pass filter circuit with an interdigital capacitor sensor as a tool for a promising technique for food and juice industries. The interdigital capacitor sensor has been designed and fabricated. The experiments have been conducted. The proposed electronic system with the interdigital capacitor sensor responds very well to different percentages of sugar content in sugar solution. The experimental results show that the suitable frequencies of the voltage source for the proposed system are the frequencies of 120-300 kHz to obtain the large output voltage differences between 10 % and 50 % sugar concentration. The interdigital capacitor sensor has the potential to be used as a sensor for inspecting sugar content in sugar solutions. The experimental results show there is a possibility of developing a novel low-cost sensing system using any microcontroller for food and juice industries. The proposed system with the sensor can also have many other potential applications, such as alcohol content determination in solutions, soil moisture content determination, and etc.

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