

# A method to determine the parameters of the double layer of a planar interdigital sensor

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**Abstract** — In this work, we present a new method for a planar interdigital transducer to determine the electrical parameters (relative permittivity, capacitance and thickness) of the double layer (DL) on the surface of the electrode loaded by a biological medium. A theoretical approach has been proposed to define these parameters. The CoventorWare software was used to simulate the model design of interdigital transducer. The simulation results show that the method can determine the parameters of double layers of a planar interdigital sensor. These results are consistent with the theoretical analysis.

**Keywords**—relative permittivity; interdigital sensor; double layer; thickness, capacitance

## I. INTRODUCTION

Characterization of biological materials can benefit from the impedance spectroscopy. Dielectric and conductive properties of biological medium depend on frequency, but the determination of these parameters is difficult. It happens because the well-known phenomenon of polarization acts at low frequency inducing error in the bioimpedance measurement and also requires a measurement device with high precision.

Bioimpedance spectroscopy is currently used in as biological measurement method. The conductivity and permittivity of the biological investigated medium could be deduced through this process. Furthermore, the bioimpedance spectroscopy allows us to obtain a database of various biological tissues conductivity and permittivity values. Since the early 1970's, many researchers have studied and published on planar interdigital sensors for different applications like surface acoustic wave devices (SAW) [1], design of microwave filters [2], optically controlled microwave devices [3], etc. More recently, the planar interdigital sensors were used notably in biomedical applications such as: impedimetric biosensing [4], detection of viable *Salmonella typhimurium* [5], detection of *Escherichia coli* O157:H7 in food samples [6], detection of avian influenza virus H5N1 [7], bioimpedance Spectroscopy [8, 9], to assess different chemicals related to food poisoning [10], to study the cellular activities of B16 melanoma cell line C57BL [11], etc.

The interdigital sensor is deposited on a glass substrate, an electric field is generated by applying a voltage between two electrodes. Indeed, the presence of an electric field is the cause of the formation of a double layer between the interface electrode and the biological medium. This double layer behaves like a capacitance interface. The interface impedance is one of

the most important constraints in bioimpedance measurements. At low frequencies, if the impedance of the interface is large, it disturbs the measurement results of the conductivity and permittivity. For this reason, the precise determination of double layer's parameters is important and allows us to optimize the geometric structure of the interdigital sensor to reduce the interface impedance.

## II. METHOD

### A. Basic concepts and definitions of the dielectric material

In general, the dielectric theory is explained based on the concept of the electrical capacitor. In a capacitor, the electrical properties of the dielectric material are maintained between two planar parallels electrodes are characterized by the capacitance (C) and the conductance (G) corresponding (see Fig. 1). When an electric voltage is applied between the electrodes, the C and the G can be determined by the following equations:

$$C = A.C_0 \text{ with } C_0 = \frac{\epsilon_0 \epsilon_r}{d} \quad (1)$$

$$G = A \frac{\sigma}{d} \quad (2)$$

where, A is the surface of the planar electrodes ( $\mu\text{m}^2$ ); d is the distance between the electrodes ( $\mu\text{m}$ );  $\sigma$  is the electrical conductivity of biological medium (S/m);  $\epsilon_0$  is the permittivity of vacuum and equal to  $\epsilon_0 = 8.8542 \times 10^{-6}$  (pF/ $\mu\text{m}^2$ );  $\epsilon_r$  is the relative permittivity of biological medium;  $C_0$  is the capacitance per unit area (pF/ $\mu\text{m}^2$ ).

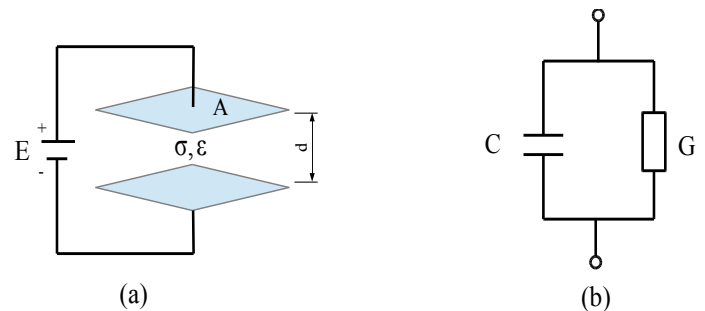


Figure 1. (a) - Dielectric biological medium between two metallic plates. (b) - Equivalent circuit of a capacitor with a conductor.

When a metal electrode is immersed into a biological medium, a double layer is formed at contact interface between electrode and biological medium. Determination of the parameters (relative permittivity, thickness) of double layer is necessary to obtain impedance measurement, which provides us with opportunity to calculate the relative permittivity and the electrical conductivity of biological medium. Furthermore, the capacitance per unit area ( $C_0$ ) of DL can be calculated by equation (1). According to Pajkossy [12] the capacitance per unit area  $C_0$  of single crystal Pt (111) surface is similar as other metals,  $C_0$  is approximately equal to 0.2 (pF/ $\mu\text{m}^2$ ).

In the work of Stern, the Gouy-Chapman model and the Helmholtz model are combined together [12, 13, 14]. Thus, the  $C_0$  is the series combination of both capacitances ( $C_{0,H}$  and  $C_{0,G}$ ):

$$\frac{1}{C_0} = \frac{1}{C_{0,H}} + \frac{1}{C_{0,G}} \quad (3)$$

where,  $C_{0,H}$  is the capacitance Helmholtz per unit area (pF/ $\mu\text{m}^2$ ) and  $C_{0,G}$  is the capacitance of Gouy-Chapman model per unit area (pF/ $\mu\text{m}^2$ ). For most physiological systems, according to Borkholder [14], Bard and Faulkner [15], the value of  $C_{0,H}$  is around 0.14 (pF/ $\mu\text{m}^2$ ) and  $C_{0,G} = 0.07$  (pF/ $\mu\text{m}^2$ ). Hence,  $C_0 = 0.047$  (pF/ $\mu\text{m}^2$ ).

#### B. Equivalent circuit model of an interdigital sensor

An interdigital sensor is fabricated by two metallic electrodes, each electrode as presented in Fig. 2 consists of a length  $L$  (mm), a width  $W$  ( $\mu\text{m}$ ), and a distance between two consecutive electrodes  $S$  ( $\mu\text{m}$ ). Then, the sensor is loaded by the investigated substance. For this sensor, a glass substrate was chosen.

Fig. 3 shows the schematic of the sensor's equivalent circuit model. The different components of biological impedance ( $Z$ ) are described by the  $C_{sol}$  and the  $R_{sol}$ . Where, the  $C_{sol}$  and the  $R_{sol}$  indicate the capacitance and the resistance of the biological medium. The  $C_{int,p}$  and the  $C_{int,n}$  are the capacitances at the contact surface of each positive and negative electrode on the contact with the biological medium. By analyzing the equivalent circuit model, we achieve the equivalent capacitance at the contact surface of the electrodes with any solution, which is determined by:

$$C_{interface} = \frac{N}{4} C_{int,p} = \frac{N}{4} C_{int,n} = \frac{N}{4} L W C_0 \quad (4)$$

where,  $N$  is number of electrodes.

In a homogeneous and isotropic medium linear material, the impedance is not a function of its electrical properties such as  $\sigma$  and  $\epsilon$ , but also depends on the geometric factors of the cell  $K_{cell}$  [15, 16] and it is described by the following expressions :

$$Z = \frac{K_{cell}}{\sigma_{sol} + j\omega \epsilon_0 \epsilon_r} \Rightarrow Y = G + j\omega C \Rightarrow \begin{cases} G = \frac{\sigma}{K_{cell}} \\ C = \frac{\epsilon_0 \epsilon_r}{K_{cell}} \end{cases} \quad (5)$$

where,  $j$  is the imaginary symbol;  $\omega$  is the angular pulsation (rad/s);  $Z$  is the complex impedance ( $\Omega$ );  $Y$  is the complex admittance (S).

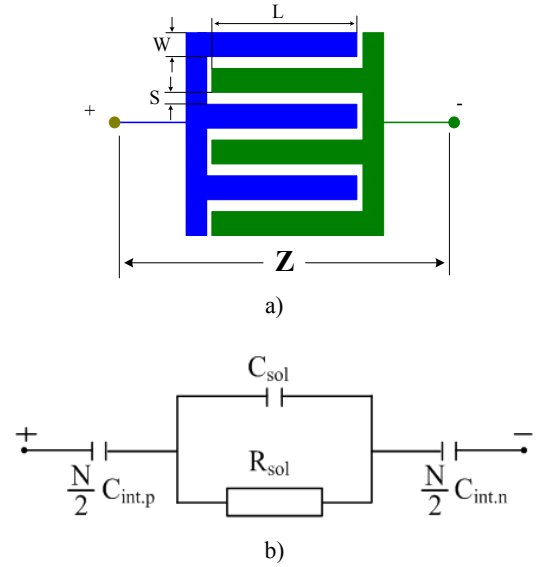


Figure 2. a) Geometric structure of an interdigital sensor. b) Simplified equivalent circuit model of interdigitalsensor

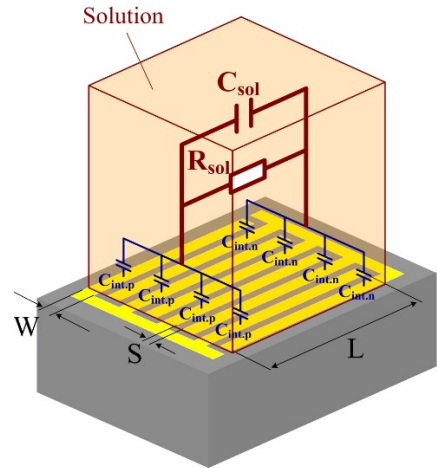


Figure 3. a) Equivalent circuit model of an interdigital sensor. The  $C_{sol}$  and the  $R_{sol}$  present the dielectric properties of the solution under testing, and  $C_{int,p}$ ,  $C_{int,n}$  indicate the properties of the double layer.

According to the equivalent electric circuit (Fig. 3), the equivalent impedance can be determined by the following formulas:

$$\begin{cases} Z = \frac{1}{G_{sol} + j\omega C_{sol}} + \frac{1}{j\omega C_{interface}} \\ Y = \frac{1}{Z} = G + j\omega C \end{cases} \quad (6)$$

By simplifying the equation (6),  $C$  can be determined as presented below:

$$C = \frac{C_{\text{interface}} G_{\text{sol}}^2 + \omega^2 C_{\text{sol}} C_{\text{interface}} (C_{\text{sol}} + C_{\text{interface}})}{G_{\text{sol}}^2 + \omega^2 (C_{\text{sol}} + C_{\text{interface}})^2} \quad (7)$$

From formula (7), when  $\omega$  is approximately equal to zero, the value of total capacity ( $C$ ) may be calculated by:

$$\lim_{\omega \rightarrow 0} C = C_{\text{interface}} \quad (8)$$

By replacing  $C$  in the equation (7) and  $C_{\text{interface}}$  in the formula (4), the equation (8) becomes:

$$\frac{\epsilon_0 \epsilon_{r,\text{low\_frequency}}}{K_{\text{cell}}} = \frac{N}{4} L W C_0 \Rightarrow C_0 = \frac{4 \epsilon_0 \epsilon_{r,\text{low\_frequency}}}{N L W K_{\text{cell}}} \quad (9)$$

From equation (9), we observe that  $C_0$  depends not only on the electric properties of medium (relative permittivity at low frequency), but also depends on the sensor's geometric. Hence, we can estimate the parameters ( $\epsilon_{r,\text{DL}}$  and  $d_{\text{DL}}$ ) of the DL. Fig.4 presents the parameters of double layer.

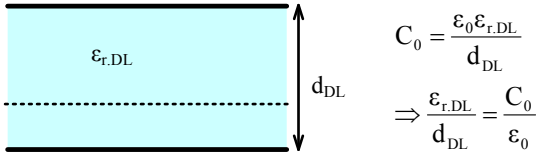


Figure 4. Parameters of double layer [18].

The relative permittivity or dielectric constant of blood at low frequency is approximately equal to 5260 and at high frequency is 60 [19]. Therefore, we can determine  $C_0$  by formula (9). Table 1 indicates  $C_0$  the parameters of DL obtained from simulation.

TABLE I. PARAMETERS OF INTERDIGITAL SENSORS AND DL

N	W ( $\mu\text{m}$ )	S ( $\mu\text{m}$ )	$K_{\text{cell}}$ ( $\text{m}^{-1}$ )	$C_0$ ( $\text{pF}/\mu\text{m}^2$ )	$\frac{\epsilon_{r,\text{DL}}}{d_{\text{DL}}} (\mu\text{m}^{-1})$
30	40	26.67	29.31	$2.7 \times 10^{-3}$	301.35
32	37.5	25	27.42	$2.9 \times 10^{-3}$	322.14
34	35.29	23.53	25.76	$3 \times 10^{-3}$	342.92
36	33.33	22.22	24.29	$3.2 \times 10^{-3}$	363.70
38	31.58	21.05	22.97	$3.4 \times 10^{-3}$	384.49
40	30	20	21.8	$3.6 \times 10^{-3}$	405
42	28.57	19.05	20.73	$3.8 \times 10^{-3}$	426.05
44	27.27	18.18	19.77	$4 \times 10^{-3}$	446.84
46	26.09	17.39	18.89	$4.1 \times 10^{-3}$	467.62
48	25	16.67	18.09	$4.3 \times 10^{-3}$	488.40
50	24	16	17.35	$4.5 \times 10^{-3}$	509

### III. MODELIZATION OF INTERDIGITATED SENSOR BY COVENTORWARE SOFTWARE

The simulation software (CoventorWare) is used to verify the theoretical results achieved in previous analysis. The main objective of this simulation is to determine the impedance of blood samples, and then we can calculate the relative permittivity. To validate our results we made a comparative study with the results of other researches.

Fig. 5 shows the 3D view of interdigital sensor. The layer 1 is a glass substrate of a square shape with dimension of  $5000 \mu\text{m}$  and a thickness of  $1000 \mu\text{m}$ . The layer 2 describes the structure of the platinum interdigitated electrodes with a thickness  $1 \mu\text{m}$ , these electrodes were deposited on the substrate and the geometric parameters of this sensor are selected:  $L = 2 \text{ mm}$ ;  $N = 40$ ;  $W = 30 \mu\text{m}$ ;  $S = 20 \mu\text{m}$ ;  $K_{\text{cell}} = 21.8$ ;  $C_0 = 3.6 (\text{pF}/\mu\text{m}^2)$ . We chose these parameters, because they have been optimized to reduce the influence of polarization in the measurement by [18]. Layer 3 describes the properties of interface polarization electric properties at the boundary between the surface of the electrodes and the blood medium with a thickness of  $1 \mu\text{m}$  ( $C_{\text{interface}}$ ). Layer 4 (with a thickness of  $500 \mu\text{m}$ ) is used to represent the electrical properties of medium. We applied a sinusoidal signal (1volt) between terminals of interdigitated electrodes, a frequency study range from 10 Hz to  $10^9$  Hz.

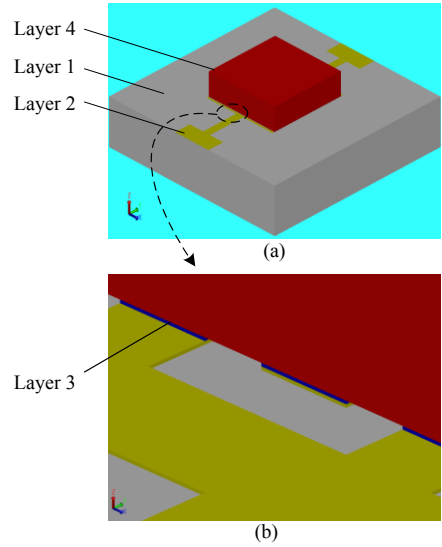


Figure 5. The 3D view of interdigital sensor (a), this sensor is deposited on a glass substrate (layer 1), layer 4 describe the dielectric properties of the blood medium. Layer 2 present the structure of the interdigitated electrodes, layer 3 indicate the double layer (b) [18].

To simulate this physical model, we used the Manhattan mesh with linear elements sized  $20 \mu\text{m}$  in the three directions (X, Y, Z) (see Fig. 6).

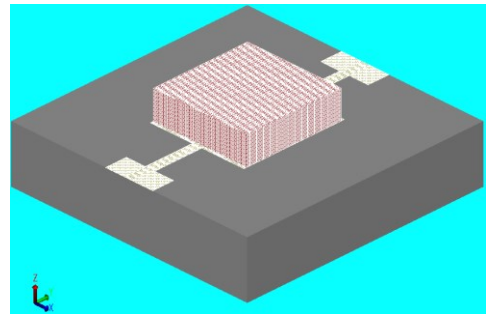


Figure 6. The schematic of sensor and Manhattan mesh model.

### IV. RESULTS AND DISCUSSION

From the geometric parameters of this interdigital sensor, we obtain the value  $C_0$  and the parameters of double layer (see table 1). Table 2 indicates the parameters of double layer to simulate.

TABLE II. PARAMETERS OF DOUBLE LAYER

Authors	$C_0$ (pF/ $\mu\text{m}^2$ )	$\frac{\epsilon_{r,DL}}{d_{DL}}$ ( $\mu\text{m}^{-1}$ )
Pajkossy	0.2	22588
Borkholder; Bard and Faulkner	0.047	5308
Our results	$3.6 \times 10^{-3}$	405

The impedance measurement could be deduced from the data C, G and frequency obtained by the Coventor software and by the following simple expression:

$$Z = \frac{1}{Y} = \frac{1}{G + j\omega C} \quad (10)$$

From the equation (5), the relative permittivity  $\epsilon_r$  of the blood samples is determined by following formula:

$$Z = \frac{K_{cell}}{\sigma_{sol} + j\omega \epsilon_0 \epsilon_r} \Rightarrow \begin{cases} \sigma_{sol} = \text{real}\left(\frac{K_{cell}}{Z}\right) \\ \epsilon_r = \text{imag}\left(\frac{K_{cell}}{Z}\right) / \omega \epsilon_0 \end{cases} \quad (11)$$

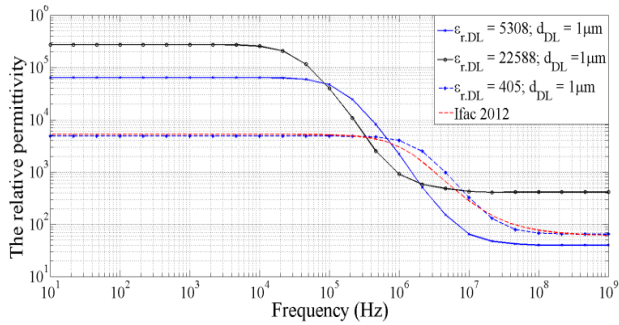


Figure 7. The permittivity as a function of the frequency

Fig. 7 shows the relative permittivity as a function of the frequency. In this figure, the curve of the relative permittivity is more similar to the curve obtained in [19]. The result of blood's relative permittivity is approximately equal to 5260 at low frequency and 65 at the high frequency. This justifies that the method to determine the parameters of the double layer of a planar interdigital sensor is correct.

#### CONCLUSION

This paper presents a physical model of interdigitated sensor in the frequency range  $10\text{--}10^9$  Hz. The theoretical approach is proposed to determine the parameters of the double layer of a planar interdigital sensor.

By analyzing the equivalent circuit model we conclude that the capacitance per unit area depends on the medium electrical properties and also the sensor's geometrical parameter. The determination of  $C_0$  permits to deduce the values of double layer.

Finally, this paper introduces a comparative approach for simulation of biological sensor modeling using CoventorWare software. The 3D interdigital sensor simulation techniques were

done to analyze the influence of the physical properties of the medium and the geometric parameters of the sensor with respect to  $C_0$ .

#### REFERENCES

- [1] J. S. Wei, "Distributed Capacitance of and Acoustic Surface," no. 4, pp. 152–158, 1977.
- [2] G.D.Alley, "Interdigital Capacitors and Their Application to Lumped-Element Microwave Integrated Circuits," *IEEE Transactions on Microwave Theory and Techniques*, vol. 18, no. 12, pp. 1028–1033, Dec-1970.
- [3] P. R. Herczfeld, "Special issue on applications of lightwave technology to microwave devices," *IEEE-INST Electr. Electron. Eng. INC*, vol. 38, no. 5, pp. 465–466, 1990.
- [4] W. Laureyn, D. Nelis, P. Van Gerwen, K. Baert, L. Hermans, and R. Magnee, "Nanoscaled interdigitated titanium electrodes for impedimetric biosensing," pp. 360–370, 2000.
- [5] L. Yang, Y. Li, C. L. Griffis, and M. G. Johnson, "Interdigitated microelectrode (IME) impedance sensor for the detection of viable *Salmonella typhimurium*," *Biosens. Bioelectron.*, vol. 19, no. 10, pp. 1139–47, May 2004.
- [6] M. Varshney and Y. Li, "Interdigitated array microelectrode based impedance biosensor coupled with magnetic nanoparticle-antibody conjugates for detection of *Escherichia coli* O157:H7 in food samples," *Biosens. Bioelectron.*, vol. 22, no. 11, pp. 2408–14, May 2007.
- [7] R. Wang, Y. Wang, K. Lassiter, Y. Li, B. Hargis, S. Tung, L. Berghman, and W. Bottje, "Interdigitated array microelectrode based impedance immunosensor for detection of avian influenza virus H5N1," *Talanta*, vol. 79, no. 2, pp. 159–64, Jul. 2009.
- [8] M. Ibrahim, J. Claudel, D. Kourtiche, and M. Nadi, "Geometric parameters optimization of planar interdigitated electrodes for bioimpedance spectroscopy," *J. Electr. Bioimpedance*, vol. 4, no. 1, pp. 13–22, Mar. 2013.
- [9] B. A. and M. N. M. Ibrahim, J. Claudel, D. Kourtiche, "Physical and Electrical Modeling of Interdigitated Electrode Arrays for Bioimpedance Spectroscopy," in *New Developments and Applications in Sensing Technology*, 2011, pp. 169–189.
- [10] A. R. M. Syaifudin, S. Member, S. C. Mukhopadhyay, P. Yu, M. J. Hajisheikh, C. Chuang, and J. D. Vanderford, "Measurements and Performance Evaluation of Novel Interdigital Sensors for Different Chemicals Related to Food Poisoning," vol. 11, no. 11, pp. 2957–2965, 2011.
- [11] A. Avram, C. Marculescu, C. M. Balan, C. Voitincu, C. Pirvulescu, M. Volmer, A. Popescu, M. Mihalescu, and M. Avram, "Microbiosensor for electrical impedance spectroscopic study of melanoma cells," *CAS 2012 (International Semicond. Conf.)*, pp. 165–168, Oct. 2012.
- [12] T. Pajkossy and D. M. Kolb, "Double layer capacitance of Pt(111) single crystal electrodes," *Electrochim. Acta*, vol. 46, no. 20–21, pp. 3063–3071, Jul. 2001.
- [13] R. Pradhan, A. Mitra, and S. Das, "Extended Stern Model," pp. 74–78, 2012.
- [14] David A. Borkholder, *Cell based biosensors using*. 1998.
- [15] A. J. Bard, L. R. Faulkner, E. Swain, and C. Robey, *Fundamentals and Applications*. .
- [16] Juan Prado Olivarez, "Conception et réalisation d'un microsystème de mesure par spectroscopie de bioimpédance," Thèse de l'Université Henri Poincaré - Nancy 1, 2006.
- [17] Laurent Bernard, "Caractérisation électrique des tissus biologiques et calcul des phénomènes induits dans le corps humain par des champs électromagnétiques de fréquence inférieure au GHz .," Thèse de l'Ecole Centrale de Lyon, 2007.
- [18] T.-T. Ngo, H. Shirzadfar, D. Kourtiche, and M. Nadi, "A Planar Interdigital Sensor for Bio-impedance Measurement: Theoretical analysis, Optimization and Simulation," *J. Nano- Electron. Phys.*, vol. 6, no. 1, pp. 1–7, 2014.
- [19] Ifac 2012, "Calculation of the Dielectric Properties of Body Tissues in the frequency range 10Hz-100GHz." [Online]. Available: <http://niremf.ifac.cnr.it/tissprop/htmlclie/htmlclie.htm#stsfatg>