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Note: Hybrid- π model and parameter extraction method for electrode-electrolyte interface characterization with superbly accurate reactance

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This paper presents an equivalent circuit model for the electrode-electrolyte interface and aims at improving the modeling accuracy of the parasitic effects at frequencies up to 300 MHz. Different from the conventional model, the electrode inductances, body loss capacitances, and body loss resistances are all included in the proposed hybrid- π model. In addition, the S-parameters obtained by a vector network analyzer are innovatively used to extract the parameters of the electrode-electrolyte interface model for a frequency range from 10 Hz to 300 MHz. Since reactance is proportional to frequency, the proposed technique can precisely calculate the parasitic effects at higher frequencies. Verified by experiments, the hybrid- π model presents better accuracies when fitted to both the phases and magnitudes of S11 and S21. The superb modeling accuracy of this work is beneficial for biomedical applications that have an electrode-electrolyte interface. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4997726>]

Microelectrodes are widely used in micro-electrical stimulation and recording systems for physiological studies and clinical treatments, such as deep brain stimulation,^{1,2} retinal/cochlear prosthesis,^{3,4} functional electrical stimulation,⁵ and peripheral/vagus nerves^{6,7}. In these applications, the impedance of electrode-electrolyte interface plays a significant role since it directly affects the efficiency of current delivery, life of battery, thresholds of stimulation systems, etc.^{8,9} An equivalent circuit is commonly used to electrically describe and model the characteristics of the electrode-electrolyte interface, which confers great benefits in biomedical studies, circuit designs, impedance monitoring, etc. An equivalent circuit model with precise fitting to the practical behavior of the electrode-electrolyte interface is therefore crucial.^{18–21}

Many methods to characterize the electrode-electrolyte interface have been reported in the literature. Electrochemical impedance spectroscopy (EIS) and NanoZ impedance tester have been explored for impedance characterization.^{10–13} The maximum measurable frequencies of these methods are limited to 10 MHz.¹⁴

However, such a low frequency measurement cannot satisfy the requirements of many biomedical applications; for example, the stimulation frequency of near deep brain stimulator is up to 127 MHz.^{15–17} The low testing frequency will therefore impede the derivation of accurate reactance in these biomedical stimulation/recording systems.

On the other hand, among the above-mentioned studies, the Randle cell model^{22,23} has been widely used to match the measured data of the electrode-electrolyte interface. It comprises an active electrolyte resistance R_{sp} , a faradaic resistance R_f , and a double layer capacitance C_{dl} . There is however a lack

of components in the Randle cell model to fully account for the parasitic factors in the practical situations, which can be evidently observed at higher frequencies.

In addition to the components already available in the Randle cell model, this paper proposes a hybrid- π model to account for the reactance of the electrode and body losses. In addition, compared to the various reported characterization methods^{10–13} that engaged the real/imaginary values of the electrode-electrolyte interface impedance at different low frequencies under 10 MHz, we propose to use the S-parameters to characterize the component values of the model. The S-parameters of the electrode-electrolyte interface are obtained via a Vector Network Analyzer (VNA). Through this approach, the measurements can be conducted at continuous frequencies from the Hz to GHz region, allowing the S-parameters to capture even more accurately the reactance than using the EIS and NanoZ impedance tester. Considering that the frequencies for many biomedical applications are less than 300 MHz,¹⁶ the experiment frequency of the VNA is chosen from 10 Hz to 300 MHz. The experiments conducted in this work have proven that the proposed method outperforms the Randle cell model (by the NanoZ method) in the MHz frequencies when fitted to both phases and magnitudes of the measured S11 and S21. This reveals that the hybrid- π model is more suitable for modeling the characteristics of the electrode-electrolyte interface than the Randle model in high frequency applications. The proposed method is especially useful for a wide range of biomedical applications operating in the range from 10 Hz to 300 MHz.

To measure the electrode-electrolyte impedance characteristics, VNA E5061B from Agilent Technologies was used for testing. The VNA was calibrated before conducting the tests. Figure 1 shows the measurement setup. In most of the biology stimulation and recording systems, an electrode cell consists of a reference electrode (RE), a working electrode (WE), and a counter electrode (CE), where the RE is usually

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FIG. 1. Setup of the proposed measuring method: (a) photograph of the system, (b) illustration of the 3-electrode system in the measurement.

connected to ground. In the experiment, the electrode cell was dipped into a phosphate buffer solution (PBS) liquid. Here, the PBS is recognized as a proper substitute of human/animal electrolyte in biomedical studies.^{10–12} As shown in Fig. 1, the WE and CE were connected to the VNA via a pair of 50- Ω RF cables. The two-port S-parameters were measured from 10 Hz to 300 MHz.

Similar to the real electrodes, the hybrid- π model shown in Fig. 2(b) is a reciprocal circuit, where the impedances seen from both ports are identical. The model comprises a double-layer capacitance C_{dl} in parallel with a charge transfer resistance R_t of the electrolyte between the two electrodes, just as the Randle model [shown in Fig. 2(a)]. Different from the Randle model, a pair of inductor-resistor, L_p - R_{sp} , is used to model the inductance and resistance introduced by the electrodes. In addition, a pair of shunt resistor-capacitor, R_b - C_b , accounts for the body effects. R_b - C_b creates a signal path to ground to model the signal losses through the electrolyte.

The measured S-parameter from the VNA is depicted in Fig. 3. A maximum testing frequency of 300 MHz, which is higher than 10 MHz, can help accurately defer the parasitic reactance since the reactance is proportional to the frequency. Here, in Fig. 3(a), it can be observed that the amplitude of S_{11} presents a dip at around 175 MHz. Correspondingly, a sharp phase step can be seen in the phase of S_{11} , as shown in Fig. 3(b). Theoretically, the amplitude dip and the phase step occur when both inductance and capacitance exist in a circuit. The 175 MHz value is around the resonant frequency caused by the inductance and capacitance. Note that this reactance phenomenon cannot be found in measurements using EIS

FIG. 2. Models for the electrode-electrolyte interface: (a) the Randle model and (b) the proposed hybrid- π model.

FIG. 3. S-parameters obtained by the measurement, proposed equivalent circuit model, and Randle model: (a) magnitude of the S_{11} parameter, (b) magnitude of the S_{21} parameter, (c) phase of the S_{11} parameter, (d) phase of the S_{21} parameter.

TABLE I. Parameters of the hybrid- π model.

R_b (Ω)	L_p (nH)	R_t (k Ω)	C_{dl} (pF)	R_{sp} (Ω)	C_b (pF)
180	33.5	300	2.3	4.8	13.4

TABLE II. Parameters of the typical Randle model.

R_{sp} (k Ω)	C_{dl} (pF)	R_t (k Ω)
9.3	13.4	300

or NanoZ, as their maximum measurable frequencies stop at 10 MHz.

The model parameters can be obtained using the Agilent Advanced Design System (ADS) tool. The obtained component parameters of the hybrid- π model are tabulated in Table I. To compare this work with the state-of-the-art studies, we first measured the same electrode cell setup using the NanoZ impedance tester and then extracted the Randle cell model [see Fig. 2(a)] with the measurement data under different frequencies using the NanoZ tester. The obtained values of R_{sp} , R_t , and C_{dl} are listed in Table II.

The S-parameters of the obtained hybrid- π model and Randle cell model are plotted with respect to the measurement in Fig. 3. At frequencies below 10 MHz, the measurement results and two model simulation results nearly overlap. What is more, the three curves start from the same point in all figures of phases and magnitudes of S11 and S21, which means that the hybrid- π model and Randle cell model are equally accurate near the zero frequency. However, when the frequency rises, the S-parameter of the hybrid- π model shows good correlations with the measurement data across the entire frequency range, whereas the S-parameter of the Randle cell model deviates significantly in the magnitude/phase of S11 and the magnitude of S21. Compared to the Randle cell model, the inclusion of several reactance components makes the proposed hybrid- π model succeed at high frequencies up to 300 MHz. The added complexity is worthwhile for applications at frequencies over 10 MHz.

In conclusion, the novel hybrid- π model and the proposed characterization method have been elaborated. The proposed methodology can extract the interface characterization at continuous frequencies from 10 Hz to 300 MHz, allowing the

observation of parasitic reactance more accurately. Despite the components in the convention Randle model, the hybrid- π model includes the electrode inductances and body losses. Proven by experiments, the hybrid- π model provides equal accuracy as compared to the Randle cell model at frequencies below 10 MHz; but in the MHz frequency ranges, the proposed hybrid- π model evidently outperforms the Randle cell model. Hence, this work is very useful for high frequency studies of electrode-electrolyte interfaces, designs of interfacing circuits, and more.

- ¹J. Lee, H.-G. Rhew, D. R. Kipke, and M. P. Flynn, *IEEE J. Solid-State Circuits* **45**(9), 1935 (2010).
- ²E. V. Arocho-Quinones, M. J. Hammer, J. M. Bock, and P. A. Pahapill, *Surg. Neurol. Int.* **8**, 22 (2017).
- ³K. Chen, Z. Yang, L. Hoang, J. Weiland, M. Humayun, and W. Liu, *IEEE J. Solid-State Circuits* **45**(9), 1946 (2010).
- ⁴R. Kwok, *Nature* **497**, 7448 (2013).
- ⁵F. Quandt and F. C. Hummel, *Exp. Transl. Stroke Med.* **6**, 9 (2014).
- ⁶S. Lee, S. Sheshadri, Z. Xiang, I. Delgado-Martinez, N. Xue, T. Sun, N. V. Thakor, S.-C. Yen, and C. Lee, *Sens. Actuators, B* **242**, 1165 (2017).
- ⁷D. R. Hulsey, J. R. Riley, K. W. Loerwald, R. L. Rennaker, M. P. Kilgard, and S. A. Hays, *Exp. Neurol.* **289**, 21 (2017).
- ⁸Y. Hong *et al.*, in IEEE International Symposium on Integrated Circuits (ISIC), Singapore, December 2016.
- ⁹Y. Hong, Y. Wang, W. L. Goh, Y. Gao, and L. Yao, in IEEE International Conference EMBC, Milano, Italy, August 2015.
- ¹⁰A. M. Dymond, *IEEE Trans. Biomed. Eng.* **23**(4), 274 (1976).
- ¹¹T. Matsubara, M. Ujje, T. Yamamoto, M. Akahori, Y. Einaga, and T. Sato, *Proc. Natl. Acad. Sci. U. S. A.* **113**(32), 8981 (2016).
- ¹²X. Qin, S. Xu, L. Deng, R. Huang, and X. Zhang, *Biosens. Bioelectron.* **85**, 957 (2016).
- ¹³X. F. Wei and W. M. Grill, *J. Neural Eng.* **6**(4), 046008 (2009).
- ¹⁴A. Hartov, T. E. Kerner, M. T. Markova, K. S. Osterman, and K. D. Paulsen, *Physiol. Meas.* **22**(1), 25 (2001).
- ¹⁵L. Golestanirad, L. M. Angelone, M. I. Iacono, H. Katnani, L. L. Wald, and G. Bonmassar, *Magn. Reson. Med.* (published online).
- ¹⁶H. N. Mayrovitz, A. Grammenos, K. Corbitt, and S. Bartos, *Clin. Physiol. Funct. Imaging* **37**, 198 (2017).
- ¹⁷H. N. Mayrovitz, A. Grammenos, K. Corbitt, and S. Bartos, *Skin Res. Technol.* **22**, 81 (2015).
- ¹⁸F. Gao, Y. Zheng, and Q. Zheng, *Med. Phys.* **41**, 053302 (2014).
- ¹⁹Y. Wang, W. L. Goh, K. T. C. Chai, X. Mu, Y. Hong, P. Kropelnicki, and M. Je, *Review of Scientific Instruments* **87**(4), 045004 (2016).
- ²⁰F. Gao, Y. Zheng, X. Feng, and C.-D. Oh, *Appl. Phys. Lett.* **102**, 063702 (2013).
- ²¹Y. Wang, Y. Hong, W. L. Goh, and X. Mu, *Review of Scientific Instruments* **87**(10), 106101 (2016).
- ²²W. Franks, I. Schenker, P. Schmutz, and A. Hierlemann, *Biomed. Eng.* **52**(7), 1295 (2005).
- ²³D. Boinagrov, X. Lei, G. Goetz, T. I. Kamins, K. Mathieson, L. Galambos, J. S. Harris, and D. Palanker, *IEEE Trans. Biomed. Circuits Syst.* **10**(1), 85 (2016).