A RF Sensor for in vivo Measurements of the Dielectric Properties of Anisotropic Tissue

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***Abstract*—In this paper, a new sensor is proposed for the dielectric properties in vivo measurement of anisotropic tissue in radio frequency band. The simulative studies were performed at frequency ranged from 10MHz to 150MHz, which validated the potential ability of this sensor in vivo measurement of dielectric properties of anisotropic tissue. According to the simulative results, several technical expatiations were given, e.g. the influence of energy coupling and the sensor sensitivity to different anisotropy ratios with different probe dimension designs. Equivalent circuit model was proposed to calculate the dielectric properties of anisotropic tissue, results shows that the relative error of measurement can be kept blow 12%. This novel sensor may indicate the dielectric properties of anisotropic tissue conveniently and accurately in radio frequency band.**

I. INTRODUCTION

THE dielectric properties of biological tissues as well as its frequency behavior, which are very important physical factors of electromagnetic responses, are the base of not only applied research in medicine such as the diagnosis and therapy of disease, but basic research in biology. There has been a lot of interest in dielectric properties measurement of biological tissues for several decades [1][2], including the in vivo measurement of anisotropic tissues. That is because the dielectric properties of some tissues, such as muscle, exhibit a great deal of anisotropy due to their microcosmic structure. Epstein and McCrae measured the anisotropic electrical properties of skeletal muscle [3][4]. Peters et al ever constructed an effective model to predict the dielectric properties of different tissues and predicted the conductivity of muscle tissue to be anisotropic [5].

Although a considerable amount of results have been accumulated, there is a continuing need for further study to fill in the blanks of dielectric properties of anisotropic tissues. Most measurements were performed by electrode [6][7], which were achieved just in the frequency below MHz. It appears that the radiation of electrode would affect the measurement results. Consequently, it has rarely been considered that measurement by electromagnetic fields in higher frequency. As well as, even current measurements also did not achieve the agreement on several conclusions. An anisotropy ratio, which is the ratio of the longitudinal conductivity to transverse conductivity, of 6.6 reported on the skeletal muscle of frog in frequencies of 20 Hz to 200 kHz [3]. While Hart and Dunfee only obtained a conductivity anisotropy ratio of 2 to 3 for frog skeletal muscle [8]. It is not clear that the certain reason of this large difference. However, the conventional probes used in these studies had to measure twice or even more in different directions for the anisotropic tissues. This would introduce error because the state of tissue would be different in each measurement. As a result, it is necessary to propose an accurate and convenient method for dielectric properties in vivo measurement of anisotropic tissues, especially in high frequency.

This study presents a new sensor for the dielectric properties in vivo measurements of anisotropic tissue in radio frequency band. The sensor would achieve the anisotropy measurement in two directions only by single measurement. Simulations were performed in frequency range from 10MHz-150MHz by FDTD to give the expatiation of several techniques including the probe dimension design, energy coupling and the sensor sensitivity to the different anisotropy ratios. As well as, the equivalent circuit model was introduced as the analysis model for measurement that attained the good results.

II. METHODS

A. The sensor description

The configuration of new sensor for the dielectric properties in vivo measurement of anisotropic tissue is shown in Fig. 1.

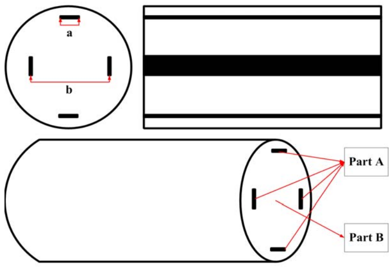

Fig. 1. The configuration of measurement probe

As shown in Fig. 1, the sensor consists of mainly two parts. Part A is two groups of opposite metal plates and Part B is dielectric material such as Teflon. In measurement, the probe is terminated with the sample. The other port is connected to

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the network analyzer by coaxial-cable. Impedance transformation would be introduced to make characteristic impedance of the probe match to the standard coaxial-cable. The perpendicular electromagnetic fields are generated respectively by Part A. The reflection coefficients in two perpendicular directions would be derived only by single measurement. These data could be related to the dielectric properties of anisotropic material.

B. The probe dimension design

There are two main parameters should be considered when designing the probe. As shown in Fig. 1, one is the width of metal plate defined to be variable a. The other is the distance between two opposite metal plates defined to be variable b. Both two dimension parameters could affect the measurement results by several factors, such as the energy coupling between two groups of opposite metal plates in perpendicular direction and the sensitivity to anisotropy of materials.

In the simulation, coupling energy between two groups of opposite metal plates in perpendicular direction with the changing of probe dimension was investigated in the frequency ranged from 10MHz to 150MHz. The probe was terminated with air. It is found from Fig. 2(a) that the coupling energy would decrease with the width of metal plate decreasing. The increase in distance between the two opposite metal plates could also reduce the coupling energy, as shown in Fig. 2(b).

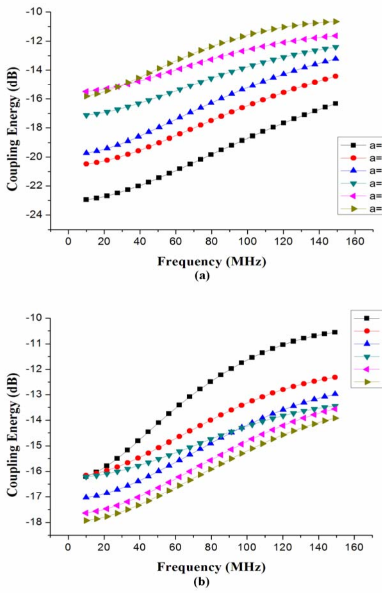

Fig. 2. Coupling energy between the two parts of opposite metal plates in perpendicular direction changing as the probe dimension: (a) variation of plate width a (b=1.3 cm) (b) variation of distance between the two opposite metal plates b (a=1.0 cm)

However, another simulation was performed in the frequency band 10MHz-150MHz to study the relationship between the probe dimension and the probe sensitivity to anisotropy of sample. The sensitivity is another factor influencing the measurement results. The probe was terminated by anisotropic material with an anisotropy ratio of 3, and the results are shown in Fig. 3 and 4.

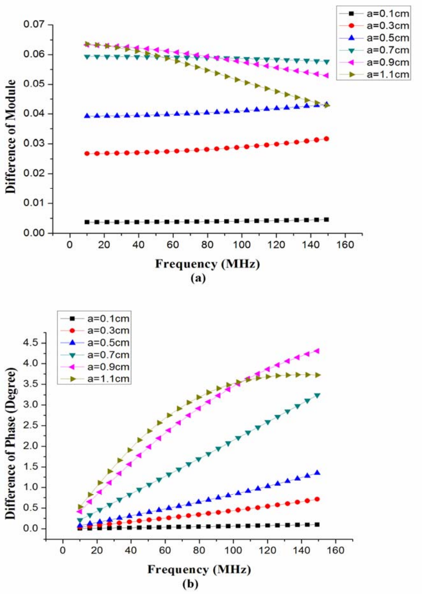

Fig. 3. Probe sensitivity to the anisotropy of sample changing as the plate width a (b=1.3 cm): (a) the difference of reflection coefficient module in perpendicular direction (b) the difference of reflection coefficient phase in perpendicular direction

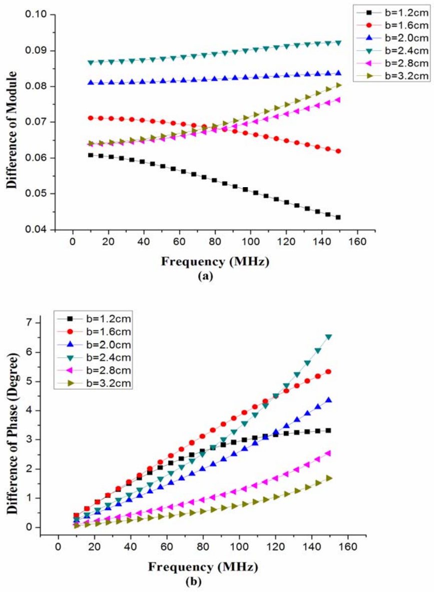

Fig. 4. Probe sensitivity to the anisotropy of sample changing as distance between the two opposite metal plates b (a=1.0 cm): (a) the difference of reflection coefficient module in perpendicular direction (b) the difference of reflection coefficient phase in perpendicular direction

As shown in Fig. 3, the increase in width of metal plate would advance the sensitivity to anisotropy of sample. However, it is found from Fig. 4 that the sensitivity was not always improved as the increase in distance between the two opposite metal plates. It was derived best when b was set to be 2.4 cm.

According to the conclusions previous, the dimension parameters a and b should be designed carefully to decrease the effect of energy coupling and derive suitable sensitivity to anisotropy of sample when the probe is designed. Actually, it is also impossible to make the dimension of probe very large for measuring the dielectric properties of biological tissues in vivo. That is because many samples from tissues only have small dimension. As a consequence, the parameter a was set to be 0.26 cm and b was set to be 1.6 cm in this paper considering the demand of actual measurement, energy coupling and sensitivity to anisotropy of sample. The coupling energy of this probe is shown in Fig. 5.

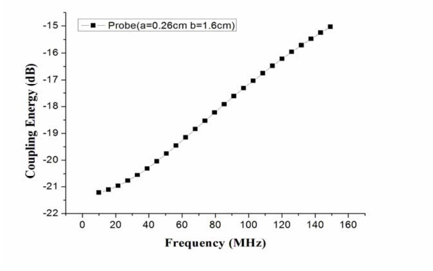

Fig. 5. Coupling energy of the probe designed in this paper (a=0.26 cm, b=1.6 cm)

C. The equivalent circuit model

When the probe is used for measurement in radio frequency band, a simple lumped parameter model could be introduced for analysis. That is because the working wavelength is much larger than dimension of probe which is called electrically small dimension. Fig. 6(a) presents the equivalent circuit model.

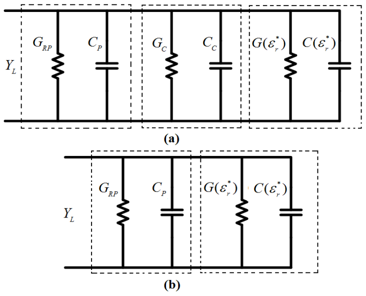

Fig. 6. The equivalent circuit of the probe: (a) primal circuit (b) simplified circuit

As shown in Fig. 6(a), G_{RP} is radiation conductance of probe caused by the aperture between metal plates, and C_P is the equivalent capacitance of probe. Both of which are only relative with the characters of probe. G_C and C_C are coupling conductance and capacitance which present the energy coupling between the two groups of opposite metal plates in perpendicular direction. While the dielectric properties of sample are included in probe terminal radiation conductance $G(\varepsilon^*_r)$ and terminal capacitance $C(\varepsilon^*_r)$ where ε^*_r is the complex permittivity of the sample. When the parameters a and b were set to be the same as results previous that made the coupling energy be below 15dB, G_C and C_C could be ignored. As a result, the circuit was simplified, as shown in Fig. 6(b). And the admittance Y_L measured from terminal port of the probe could be calculated as follow:

$$Y_L = G_{RP} + G(\varepsilon_r^*) + j\omega C(\varepsilon_r^*) + j\omega C_P \tag{1}$$

In fact, probe terminal circuit components $G(\varepsilon^*_r)$ and $C(\varepsilon^*_r)$ present the same as the coaxial open-ended probe described in [9]. Consequently they are given as:

$$\begin{aligned} G(\varepsilon_r^*) &= G_0 \varepsilon_r^{*5/2} \\ C(\varepsilon_r^*) &= C_0 \varepsilon_r^* \end{aligned} \tag{2}$$

Parameters G_0 and C_0 are terminal radiation conductance and capacitance when the probe is terminated with air. As a result, (1) could be changed as:

$$Y_L = G_{RP} + G_0 \varepsilon_r^{*5/2} + j\omega C_0 \varepsilon_r^* + j\omega C_P \tag{3}$$

According to (3), the parameters G_{RP}, C_P, G_0 and C_0 could be determined empirically from measurements on two well-known materials such as water, saline and so on. After that, the complex permittivity of the test sample could be solved by (3).

III. RESULTS

Several anisotropic materials described in Table 1 were used in simulation to confirm the measurement ability of this probe. To simplify the analysis, the anisotropy of materials in the perpendicular direction was considered. The materials were set to be a cylinder with diameter of 4 cm and thickness of 3 cm. That is large enough for the biology tissues measurement. The probe was terminated with samples in z-axis direction, and the dielectric properties of these anisotropic materials could be solved according to the reflection coefficient in x-axis and y-axis direction. The simulation was performed at frequency ranged from 10MHz to 150MHz. 0.1M NaCl solution and air were used to determine the parameters G_{RP}, C_P, G_0 and C_0 in (3). Fig. 7 shows the measurement results by this probe.

As shown in Fig. 7(a), the permittivity relative error was below 8%. While the conductivity relative error was below 12% exhibited in Fig. 7(b). Although, it was found that both the permittivity and conductivity relative error increased with the frequency. The results were still acceptable for measurement.

TABLE I
THE ANISOTROPIC MATERIALS FOR SIMULATION

Materials	Permittivity	Conductivity
Mat A	$\varepsilon_{rx} = \varepsilon_{rz} = 15$ $\varepsilon_{ry} = 60$	$\sigma_x = \sigma_z = 0.2$ $\sigma_y = 0.8$
Mat B	$\varepsilon_{rx} = \varepsilon_{rz} = 45$ $\varepsilon_{ry} = 50$	$\sigma_x = \sigma_z = 0.2$ $\sigma_y = 1.2$
Mat C	$\varepsilon_{rx} = \varepsilon_{rz} = 73$ $\varepsilon_{ry} = 90$	$\sigma_x = \sigma_z = 0.6$ $\sigma_y = 0.2$

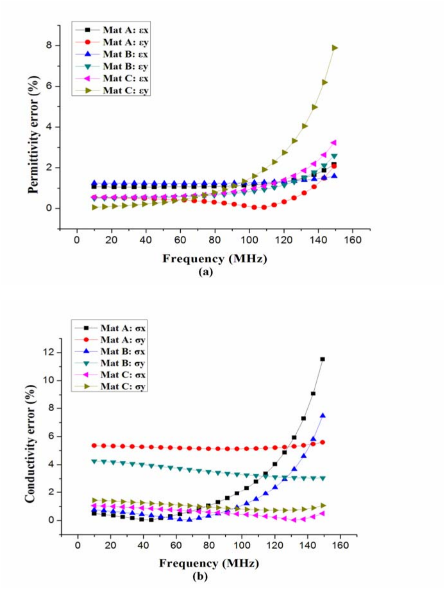

Fig. 7. The dielectric properties simulation results of materials in table 1 by the probe designed in this paper (a=0.26 cm, b=1.6 cm): (a) permittivity error (b) conductivity error

IV. DISCUSSION

This new RF sensor is similar to the four-electrode probe used in the biological impedance measurement as described by Laufer [10]. However, it could be found that the electrode of new probe was not designed to be needle but plate as described in Fig. 1. That is because the single directional polarization should be generated to distinguish the responses in different directions when measuring the anisotropy of material. As a result, the electrode of this probe should be kept wide enough for the single directional polarization to derive suitable sensitivity to anisotropy of sample that accords with the conclusion in Fig. 4.

The equivalent circuit model was used in this paper for the analysis. That is because it would be complex to analyze the distributing of electromagnetic fields in this probe. The field does not only concentrate in the probe but radiate outside, which was not the same with conventional sensor. And the fringe effect of electrodes would also make the analysis more difficult. Therefore, it is more suitable and convenient to use the circuit model for analysis.

The energy coupling between two groups of opposite metal plates in perpendicular direction is an important factor that would interfere with the measurement result. In the former simulation results, the measurement error was found to be dependent on frequency as shown in Fig. 7, which was considered resulting from the effect of coupling. However, this coupling energy could be controlled below an acceptable level by carefully design. On the other hand, the energy coupling effect of new probe would be investigated further in future research.

V. CONCLUSION

In this study, a novel sensor was presented for in vivo measurements of the dielectric properties of anisotropic tissue in radio frequency band. This probe would derive the anisotropy only by single measurement. It is much more convenient and credible than conventional method. Simulations were performed to present several technique expatiations of this probe. The suitable dimension design of this probe was discussed before measurement based on the energy coupling and sensor sensitivity to the different anisotropy ratios. As well as the simplified equivalent circuit model that ignored the energy coupling component was introduced in this paper for analysis. After measuring several anisotropic materials in simulation, good results with acceptable error were reported in which the permittivity error was below 8% and conductivity error was below 12%.

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