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MEASUREMENT OF DIELECTRIC PROPERTIES OF BIOLOGICAL SUBSTANCES USING IMPROVED OPEN-ENDED COAXIAL LINE RESONATOR METHOD

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Abstract

An improved open-ended coaxial line resonator method is presented. By considering the influences of radiation effect and higher order modes, the measurement frequency range has successfully extended to X-band. The results of seven organs of a dog have given, which can be refered in bioelectromagnetics.

Introduction

In recent years, more attention has being given to the studying of dielectric properties of biomaterials in vivo. Knowledge of the permittivity and its frequency and temperature behavior is of great importance in both basic and applied research.

Coaxial line sensor has come into wide use in measuring dielectric properties of biomaterials. However, both reflection and resonant method were restricted to frequency range below 4 GHz till now.(1),(2)

We have analysed the influence of radiation and higher order modes effect and given a concise expression.(3) In this paper, a more extensive expression of the measurement technique of resonant method is presented. Selected biological tissues and phantom muscle are measured in frequency range 0.1--10 GHz. The results are good agreement with published data.

Principle of Measurement

(1) Equivalent Circuit

Fig.1 shows an open-ended coaxial line resonator and the sample to be tested. Fig. 2 shows the equivalent circuit.

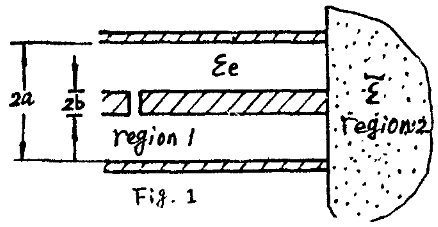

Fig.1 A coaxial line resonator

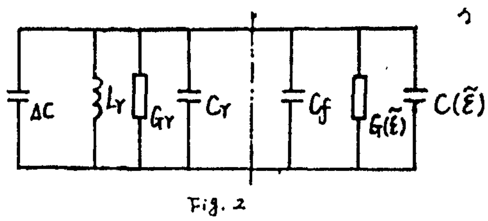

Fig.2 Equivalent circuit

Where, $C(\tilde{\varepsilon})$ and C_f represents the field concentration in region 2 and inside the coaxial line, respectively; $G(\tilde{\varepsilon})$ represents the radiation into the tested sample; ΔC is the coupling element; and the L_r, C_r, G_r are the parameters of the resonator in ideal state.

When region 2 is free space, the parameters $G(\tilde{\varepsilon})$ and B, i.e. $j\omega C$, can be calculated by following formulas:(4)

$$G/Y_0 = \frac{1}{\ln a/b}\int_0^{\pi/2}\frac{d\theta}{\sin\theta}\,(J_0(ka\sin\theta)-J_0(kb\sin\theta))^2 \qquad (1)$$

$$B/Y_0=\frac{1}{\pi \ln a/b}\int_0^{\pi}(2Si(k\sqrt{a^2+b^2-2ab\cos\varphi})-$$
$$-Si(2ka\sin\tfrac{\varphi}{2})-Si(2kb\sin\tfrac{\varphi}{2}))d\varphi \qquad (2)$$

Where, $J_0(x)$ is the Bessel function, $Si(x)$ is the sinusoidal integral function; and $k=2\pi/\lambda$

Expanding $J_0(x)$ into a Maclaurin series then yield:

$$G/Y_0=\frac{1}{\ln a/b}(G_1(f^4)+G_2(f^6)+G_3(f^8)+$$
$$+G_4(f^{10})+\ldots\ldots) \qquad (3)$$

where,

$$G_1(f^4)=2/3(a^2-b^2)\pi^4/\lambda^4 \qquad (4)$$

$$G_2(f^6)=-4/15(a^2-b^2)(a^4-b^4)\pi^6/\lambda^6 \qquad (5)$$

$$G_3(f^8)=16/35(1/16(a^4-b^4)^2+1/18(a^2-b^2)\cdot(a^6-b^6))\pi^8/\lambda^8 \qquad (6)$$

Considering the influence of higher order modes, using variational method, the fringe capacitance can be shown:

$$C_0(f)=C_{00}+\Delta C_0 f^2+\Delta C_1 f^4+\ldots\ldots \qquad (7)$$

Where, C_{00} represents the static fringe capacitance.

If region 2 is filled with dielectric material, the open-ended coaxial line can be considered as an antenna; according to the Deschampes theorem, we find the result:

$$Y(\omega,\tilde{\varepsilon}\varepsilon_0)=G(\tilde{\varepsilon})+j\omega C(\tilde{\varepsilon}) \qquad (8)$$

where,

$$G(\tilde{\varepsilon})=\tilde{\varepsilon}^{5/2}G_1(f^4)+\tilde{\varepsilon}^{7/2}G_2(f^6)+\tilde{\varepsilon}^{9/2}G_3(f^8)+$$
$$+\tilde{\varepsilon}^{11/2}G_4(f^{10})+\ldots\ldots \qquad (9)$$

$$C(\tilde{\varepsilon})\doteq C_{00}\tilde{\varepsilon}+\Delta C_0\tilde{\varepsilon}^2 f^2=C_{00}+\Delta C_0'\tilde{\varepsilon}^2 \qquad (10)$$

(2) Principle of Measurement

If region 2 is filled with air and dielectric material respectively, the resonant frequency and corresponding quality factor are denoted as f_0, Q_0 and f_1, Q_1. Using resonant condition and equation (3)--(10), we can obtain the following equations:

$$\varepsilon_r=\frac{Y_{01}\,\mathrm{ctan}\beta_1 l_{eff}+b}{\omega_1 C_{00}}-\frac{C_f+\Delta C_0'\varepsilon_r^2(1-\tan\delta)}{C_{00}} \qquad (11)$$

$$\tan\delta=k(1/Q_1-1/Q_a-1/Q_r) \qquad (12)$$

Where, C_{e1}, C_{e0} are the total capacitance of the resonant circuit, When the sensor is surrounded with tested material and air, respectively; G_{e1} is the total conductance of the circuit, when it resonate at frequency f_1, the parameters:

$$K=C_{e1}/(\varepsilon_r C_{00}+2\Delta C_0'\varepsilon_r^2) \qquad (13)$$

$$Q_a=Q_0\omega_1 C_{e1}/\omega_0 C_{e0}\ ;\ Q_1=\omega_1 C_{01}/G_{e1} \qquad (14)$$

$$Q_r=\omega_1 C_{e1}/g \qquad (15)$$

Measurement Technique

(1) Coupling Structure

A $\lambda/2$ coaxial line resonator was used by E.Tanaba.(2) By breaking the center conductor of the coaxial line, an air gap was formed and the energy is coupled through this gap.(see Fig.1) In this paper, we designed a $\lambda/4$ coaxial line resonator. the coupling structure is formed by a copper foil placed inside APC-7 connector, which connect the sensor to measurement system (Fig.3 and Fig.4). By changing the shape and size of the foil, we can achieve different coupling. It shows that this structure has

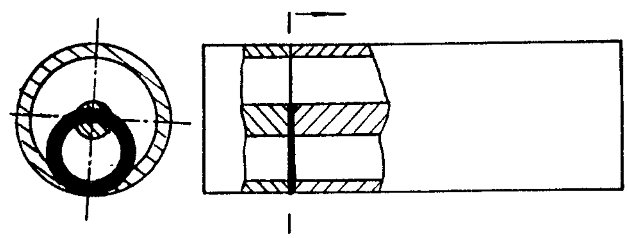

Fig.3 Coupling structure

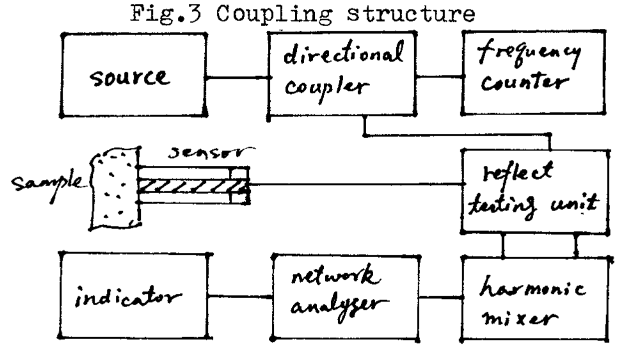

Fig.4 Measurement system

more flexible and convenience.Results of three reference samples using three different shape foils is given.It shows that the foil shape has no influence over the measured results of ε_r and $\tan\delta$.

(2) Measurement Equipment

The equipment used in the measurement is shown in Fig.4.A network analyser is used to indicate resonance and half power frequency points.The frequencies are measured with a frequency counter.

Measurement Results

Seven organs of a dog ,i.e. muscle, skin,liver,kidney,heart,grey matter and white matter of brain were measured. Room temperature is controlled within 20°C±1°C. Sample surface was large than 10mm×10mm, thickness over 5mm.

Results of measurement performed in frequency range UHF to X-band are given. It shows that the measured data are quite close to the reference data.The results of phantom muscle is also given.(see table 1)

In this paper,the computation formula is more acurate than the formula used by E.Tanaba.So,even though the measurement frequency is higher than 4GHz,the relative error $\Delta\varepsilon_r/\varepsilon_r \leq 5\%$, $\frac{\Delta\tan\delta}{\tan\delta} \leq 25\%$ are still obtainable.We have measured the dielectric properties of human skin(hand dorsum) and compared with reference data,the result shows that this conclusion is realiable.(5)-(7)

Conclusion

The improved open-ended coaxial line resonator method has many advantages.By considering the influence of radiation effect and higher order modes,the measurement frequency range have successfully extended to X-band.A thin copper foil coupling structure is developed.Its performance is excellent , reliable.The dielectric Properties of seven organs of a dog at frequency range 0.1--10 GHz have been given,which can be refered in madicine,bioelectromagnetics and other fields.

f (GHz)		Muscle	Heart	Kidney	Liver	skin	White matter	Grey matter
0.1	ε'	72.71	61.25	68.30	56.83	38.80	59.86	77.53
	ε''	126.94	82.23	96.17	57.04	51.89	62.64	111.78
0.5	ε'	61.47	56.49	59.49	57.53	45.43	37.34	63.55
	ε''	36.26	28.47	32.77	22.89	19.67	14.09	30.67
0.75	ε'	58.34	58.12	57.52	56.08	40.71	43.50	60.05
	ε''	30.22	26.03	24.54	19.77	12.46	14.61	24.27
1.0	ε'	51.97	53.00	55.77	54.62	41.05	41.19	58.79
	ε''	20.30	21.23	17.15	15.38	11.56	14.27	19.61
2.0	ε'	53.92	52.49	53.84	51.94	39.51	42.83	59.66
	ε''	17.02	17.01	16.71	15.00	11.22	11.59	18.36
3.0	ε'	52.92	51.98	53.01	49.12	39.19	38.17	55.86
	ε''	15.02	13.11	14.92	14.09	10.96	8.53	13.59
4.0	ε'	49.24	51.78	48.67	45.49	34.13	36.09	51.66
	ε''	13.97	13.05	12.83	13.53	8.68	8.05	11.76
6.0	ε'	44.10	41.46	43.90	42.14	33.07	31.32	49.52
	ε''	22.42	23.92	21.05	19.25	14.29	11.96	25.60
9.0	ε'	40.82	39.57	43.39	38.32	28.68	30.08	44.76
	ε''	26.48	26.18	29.19	25.04	16.90	13.38	29.51
11.8	ε'	35.23	28.75	30.71	32.13	25.10	23.10	30.91
	ε''	31.89	21.17	25.08	24.51	16.87	13.37	24.73

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