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Microwave Characterization of Frequency and Temperature Dependences of Beef Bone Dielectric Properties Using Waveguide Measurement System

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Abstract. *The article focuses on the measurement and calculation of dielectric properties of biological tissue in the frequency band 4,5 GHz – 16 GHz. Special attention is paid to the frequency and thermal dependence dielectric constant and loss factor. Observed frequency changes of biological tissue dielectric properties obey causality, i.e. Kramers-Krönig relationships which relate changes of dielectric constant with conductivity changes. Our results for frequency dependence of complex permittivity prove the fundamental Cole-Cole model but also the necessity to investigate the biological tissues like heterogeneous material with not only one relaxation phenomena.*

Keywords: Biological Tissues, Dielectric Properties, Microwave Frequencies, Waveguide Method.

1. Introduction

Dielectric properties of biological tissues and cell suspensions have been of interest for over a century for many reasons. They determine the pathways of current flow through the body and, thus, are very important in the analysis of wide range biomedical applications. To develop the use and additional applications of microwave energy, it must be considered that the dielectric properties of the tissues which determine the absorption and propagation of electromagnetic energy through the tissues. So from the knowledge of dielectric constant, tissue properties can be characterized in the microwave frequency range. To analyze the response of a tissue to electric stimulation, we need data on the variation of specific conductivity and relative permittivity of the tissues and organs, with the frequency and temperature changing [1].

A microscopic description of the response is complicated by the variety of cell shapes and their distribution inside the tissue as well as different properties of the extra cellular media. A macroscopic approach is most often used to characterize field distributions in biological systems. Moreover, even on a macroscopic level, the electrical properties are complicated. They can depend on the type of tissue, on the tissue orientation relative to the applied field (directional anisotropy), the frequency of the applied field (the tissue is neither a perfect dielectric nor a perfect conductor), on the tissue temperature, or they can be time- and space-dependent (e.g., changes in tissue conductivity).

2. Dielectric properties of biological tissues

Large differences exist in dielectric properties of biological materials. These differences are determined, to a large extent, by the fluid content of material. For example, blood and brain conduct electric current relatively well. Lungs, skin, fat and bone are relatively poor conductors. Liver, spleen, and muscle are intermediate in their conductivities.

The dielectric properties of biological tissues are highly dispersive due to the cellular and molecular relaxation, generated by different parts of the tissues at different frequencies. In the microwave region the dominant relaxation is the dipolar relaxation of free water molecules. Therefore, the dielectric properties of the tissues in microwave region are highly correlated to the water content. At the frequencies in microwave region (~10^9 Hz) the rotations of the polar molecules in the water begin to lag behind the electric field oscillations.

At frequencies for which the loss angle δ differs significantly from 90° the water has the dual role. It functions both as a dielectric and as a conductor and dielectric properties of materials are quantified by their bulk permittivity ε which has a complex character

$$\varepsilon = \varepsilon' - \mathrm{j}\varepsilon'' , \tag{1}$$

where the ε' is relative permittivity (dielectric constant). It is determined by the magnitude of overall net polarization in material. ε' determines the amount of energy stored per unit volume in material for a given applied field. The imaginary part in (1) is loss factor given as $\varepsilon'' = \sigma / \omega\varepsilon_0$, where σ is the electrical conductivity, ε_0 the dielectric constant for free-space and ω angular frequency. The loss factor represents the energy loss in a material and is governed by the lag in polarization upon application of the field and the energy dissipation associated with charge polarization. In solids (in our study of biological tissue) and liquids consisting polar molecules (those retaining a permanent dipole moment, e.g. water), the resonance effect is replaced by relaxation. A phenomenological approach for the mathematical modelling of dispersion is the Debye theory. The theory suggests a first order of differential equation system, similar to charge of a linear *RC* circuit. The complex permittivity in the frequency domain reduces to the Debye equation

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_\mathrm{s} - \varepsilon_\infty}{1 + \mathrm{j}\omega\tau} , \tag{2}$$

where ε_s and ε_∞ are the static and optical dielectric constants and τ , i.e. the relaxation time, that is a time constant of this first order system. Biological materials like markedly heterogeneous material do not exhibit single time constant relaxation behaviour. In concentrated systems, as well as biological tissues the electrical interaction between the relaxing species will usually lead to a distribution of relaxation time, $p(\tau)$ and with the help of this distribution, the following relation is used

$$\varepsilon = \varepsilon_\infty + (\varepsilon_\mathrm{s} - \varepsilon_\infty)\int_0^\infty \frac{p(\tau)}{1 + \mathrm{j}\omega\tau}\mathrm{d}\tau - \mathrm{j}\frac{\sigma_\mathrm{i}}{\omega\varepsilon_0} , \tag{3}$$

where σ_i is the static ionic conductivity of the medium placed in a constant field that influencing very low frequencies. To enable a more wide-band model of the properties the time constant can be divided in several regions to match different type of relaxation. Due to the complexity and composition of biological tissues [2] extended Cole-Cole model is commonly used as physically based compact representations of wideband frequency dependent dielectric properties. In this case the complex dielectric constant is

$$\varepsilon = \varepsilon_\infty + \sum_n \frac{\Delta\varepsilon_n}{1 + (\mathrm{j}\omega\tau_n)^{1-\alpha_n}} - \mathrm{j}\frac{\sigma_\mathrm{i}}{\omega\varepsilon_0} , \tag{4}$$

where $\Delta\varepsilon_n = \varepsilon_\mathrm{s} - \varepsilon_n$, and ε_n is relative permittivity appertaining to one relaxation process, α_n represents the distribution parameter which is a measure of broadening of dispersion and ionic conductivity is for microwave frequencies in (3) and (4) ignored.

Along with frequency effects, the complex permittivity is also affected by temperature. This dependence is governed by the effect of temperature on the individual polarization mechanisms [3]. Most notably, because charge mobility is affected by temperature, the electrical conductivity of a material will increase with an increase of the temperature.

3. Experimental results

For our measurement we have chosen the waveguide Hippel's method which has proved successful for the measured material and it behaves as the most accurate methods for dielectric properties of biological materials measurement. The measurements were carried out in frequency of two microwave bands - 4.5 GHz to 16 GHz. The experimental set-up for both bands are drawn in Fig. 1.

As a microwave source there was alternatively used besides the reflex klystron as well as HP broadband generator. All measurements were carried out on beef bones and the samples were taken from one homogenous part of femoral bone (without marrow). The samples were formed in such way to fit close to the waveguide walls (they were impressed into the waveguide). Different temperatures were obtained by immersion the waveguide with the sample into warmed water and the waveguide was safeguarded against water penetration into the sample, while the short - circuit was maintained.

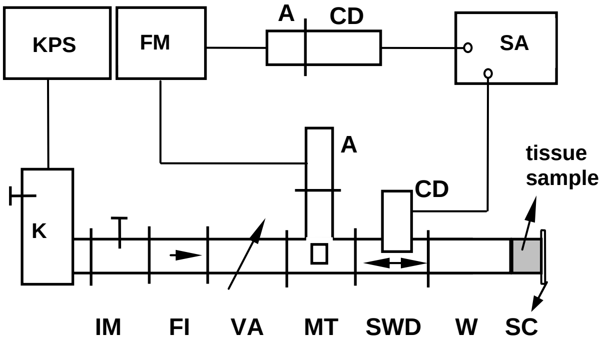
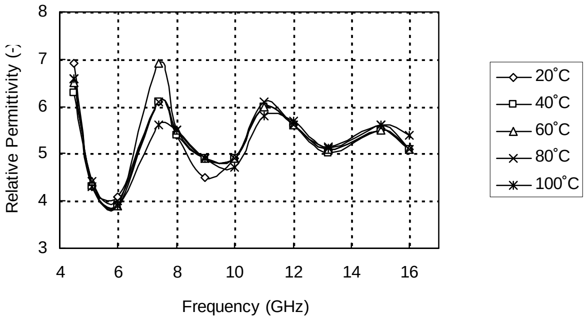


Fig. 1. Experimental set-up for complex dielectric constant measurement. K – klystron, KPS – klystron power supply, FM – frequency meter, SA – selective amplifier, IM – impedance match, FI – ferrite isolator, VA – variable attenuator, MT – magic T, SWD – slotted section, W – waveguide, SC – short circuit, A – adapter, CD – crystal detector.

The appropriate values were calculated and dependences ε' and tgδ on frequency and temperature are plotted in Fig. 2 up to Fig. 5.



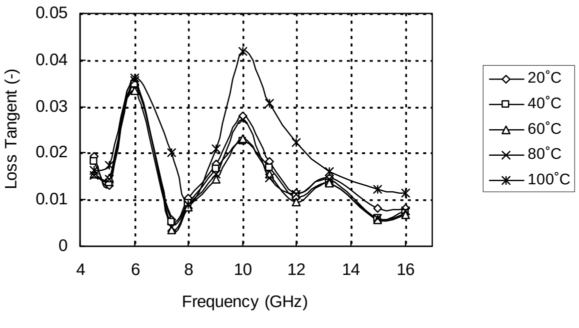


Fig. 2. Frequency dependence of relative permittivity for different temperatures.

Fig. 3. Frequency dependence of loss tangent for different temperatures.

It can be seen from the Fig. 2 and Fig. 3 that the frequency dependences of ε' and tgδ show similar courses for all temperatures. Values of ε' and ε'' cannot vary independently with frequency, since their frequency variations are connected through the Kramers-Krönig relationship: a drop in ε' with increasing frequency is necessarily associated with a peak in

ε'', Fig. 2 and Fig. 3.While the values of ε' at different temperatures remain almost constant at all measured frequencies, the values of tgδ rise at higher temperatures except the frequency 6 GHz, Fig. 4 and Fig. 5.

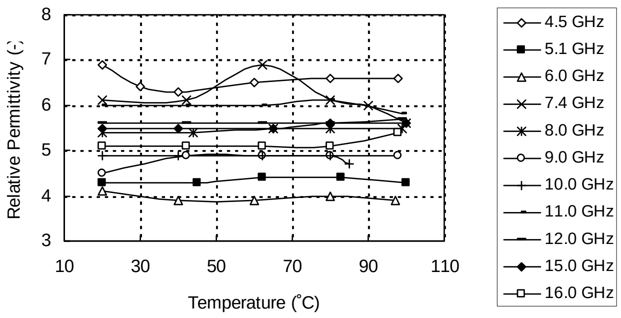


Fig. 4. Temperature dependence of relative permittivity for different frequencies

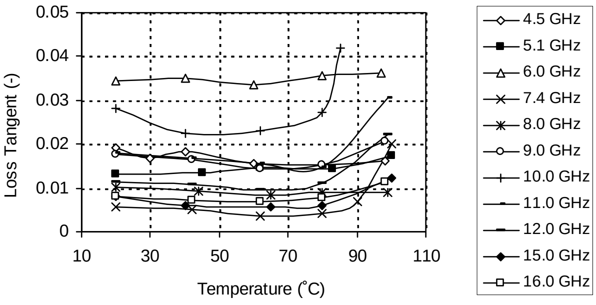


Fig. 5. Temperature dependence of loss tangent for different frequencies

The temperature dependence of relative permittivity ε' does not show expressive changes.

4. Conclusions

Although there are being published more information concerning dielectric properties different biological tissues accomplished data about bones occur only rarely. At the same time the temperature and frequency dependence of bone relative permittivity and loss tangent at the present time developing microwave therapy, will call for more detailed data about every part of human tissue. From this standpoint we have proceeded to the choice of the presented work and our results have brought some closer information for these applications. We submit data about temperature and frequency dependences more comprehensively occurring so far rather separately. Apart from that our results we point out that biological tissue is an inhomogeneous material and for the description of frequency dependence of dielectric constant a simple Cole-Cole model is not sufficient. It can be seen from our figures that several relaxation mechanisms go on simultaneously.

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