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Modelling of scattering parameters in biological tissues

Abstract*. The knowledge of electrical properties of biological materials and their interaction with electromagnetic waves is necessary for suitable determining the effect of electromagnetic field on biological systems and sequentially prevention of undesirable consequences on human organism. Because of complex heterogeneous structure of biological tissues the electromagnetic field distribution in biological systems is very complicated and depends, among others, on the type of tissue and on the presence of complicated layered structures and interfaces. With the knowledge of these electrical properties the absorption of energy and the field distribution which are the results of the solution to a boundary value problem can be obtained and simulated.*

Streszczenie. *Znajomość elektrycznych parametrów materiałów biologicznych i ich oddziaływania z falami elektromagnetycznymi jest niezbędna dla oceny oddziaływania pola na systemy biologiczne i ochrony organizmów przed jego niepożądanymi efektami. Ze względu na skomplikowaną, heterogeniczną strukturę tkanek rozkład pola elektromagnetycznego w systemach biologicznych jest skomplikowany i zależy, między innymi od rodzaju tkanki oraz jej kształtu. Znajomość tych parametrów umożliwia symulację pola elektromagnetycznego w organizmie i ustalenie wielkości absorbowanej energii. (**Modelowanie elektrycznych parametrów materiałów biologicznych**)*

Keywords: scattering parameter, heterogeneous biological structure, microwave frequencies.
Słowa kluczowe: parametry elektryczne (rozproszeniowe) tkanki, struktury biologiczne, mikrofale.

Introduction

The interaction of electromagnetic (EM) fields with the human body has been a subject of scientific interest for last decades. The knowledge of electrical properties of biological materials and their interaction with electromagnetic waves is necessary for suitable determining the effect of electromagnetic field on biological systems as well as in medical applications. The published data in the literature shows a significant contrast that exists between different types of tissues at different frequency range [1].

In this article the interaction of EM wave with biological tissue is investigated in terms of the analysis of the EM absorption and scattering properties of a multilayered structure representing simplified models of human tissues. For this investigation was created a human head model comprised of skin, fat, bone and brain layer without and with presence of brain tumour. The simulations can provide useful data about the absorption patterns in human body models.

Electromagnetic wave propagation in biological tissues

A material is lossy if its conductivity does not equal zero value. Biological tissues are lossy materials and this loss changes the way the wave interacts with the material and its propagation behavior. Power will be deposited in the lossy material as wave passes through it, thus causing loss to the propagating wave. If power is cumulated in the material, the material will heat up.

To better understand how EM power is deposited in a lossy material, considering theory of waves, Ampere's law can be written in a form

$$\nabla \times \overline{H} = (\sigma + \omega\varepsilon'')\overline{E} + \mathrm{j}\omega\varepsilon'\overline{E}, \tag{1}$$

where $\nabla \times \overline{H}$ is a mathematical expression called the curl of magnetic field intensity $\overline{H}$ (A/m), $\overline{E}$ represents electric field intensity (V/m), σ is conductivity of the material and ω is an angular frequency (rad/s). The first term on the right-hand side of this equation represents the current that produces a loss (heat) in the material through movement of free charges and bound charges. The last term in (1) is the displacement current which represents the lossless portion of the oscillation of the bound charges [2].

The loss properties of material are usually expressed as a loss tangent

$$\mathrm{tg}\,\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon'_{\mathrm{r}}\varepsilon_0}, \tag{2}$$

where σ is the electrical conductivity (S/m), $\varepsilon'_{\mathrm{r}}$ is the relative dielectric constant, $\varepsilon_0 = 8.854191\mathrm{x}10^{-12}$ (F/m) is the permittivity of free-space and ω is angular frequency of applied electromagnetic field.

Relaxation processes in biological tissues

The response of biological tissues at microwave EM field is determined by the electro-chemical characteristics of cells, cellular structure and the intra-cellular fluid too. The permittivity of biological tissues is determined by several important dispersion phenomena whose contributions are normally restricted to specific band.

In general, dispersion characteristics of a large class of biological materials can be represented by Cole-Cole equation

$$\dot{\varepsilon} = \varepsilon_\infty + \frac{\varepsilon_{\mathrm{s}} - \varepsilon_\infty}{1 + (\mathrm{j}\omega\tau)^{1-\alpha}} \tag{3}$$

where ε_∞ and ε_{s} are the relative permittivities of material at infinite and zero frequencies respectively. The (1-α) parameter represents distribution of relaxation in investigated material where α is a distribution parameter in the interval $0 \le \alpha < 1$ [3].

Scattering Parameters of Biological Tissues

Dielectric properties permittivity and conductivity of biological tissues may be determined using scattering parameters (S-parameters), Fig. 1.

The S-parameters matrix expresses the changes of EM energy propagating through a multi-port transmission line if the EM wave meets the impedance differing from the line's characteristic impedance. These S-parameters express the response to reflected ($\dot{S}_{11}$, $\dot{S}_{22}$) and transmitted ($\dot{S}_{12}$, $\dot{S}_{21}$) electromagnetic signals at each port.

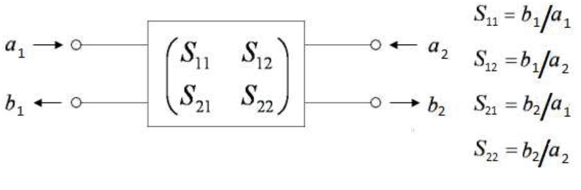

Fig.1. Generalized two-port line, a – incident signal at the port, b – reflected signal at the port

Reflection and transmission characteristics in layered structures

When there are several layers of different tissues, the reflection and transmission characteristics become more complicated. Multiple reflections occur between tissue boundaries, with a resulting modification of the reflection and transmission coefficients, Fig. 2. The transmitted wave perpendicular to the boundary interacts with the reflected wave and both form standing waves in each layer. This phenomenon becomes especially pronounced if the thickness of each layer is less than the penetration depth for that tissue.

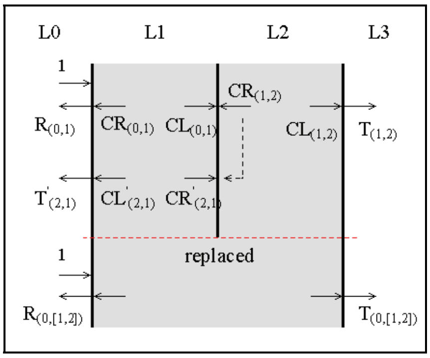

Fig. 2. Two-layered model with corresponding coefficients. CR and CL represents total sum of multiple reflections within sample

The un-dashed coefficients represents incident signal arriving from the left and the dashed ones represents incident signal arriving from the right. Then we can determine reflection and transmission coefficients

$$R_{(0,[1,2])} = R_{(0,1)} + \frac{CL_{(0,1)}CR_{(1,2)}T'_{(2,1)}}{1-CR'_{(2,1)}CR_{(2,1)}}, \tag{4}$$

$$T_{(0,[1,2])} = \frac{CL_{(0,1)}T_{(1,2)}}{1-CR_{(1,2)}CR'_{(2,1)}}. \tag{5}$$

This procedure can be applied for *n*-layered structure [4].

Modelling of scattering parameters for human head model

The human tissue is regarded as a stratified medium composed of isotropic homogeneous lossy dielectric layers. The results from simple models phantoms of biological tissue for microwave hyperthermia are not representative of the reality of different tissues, their associated shapes and boundaries, which will result in the electromagnetic propagation and power deposition rate being quite different in each tissue type. The first problem for study of selective heating in selected area within a typical body cross section is the determination of the electromagnetic power deposition within the heterogeneous tissue volume and also investigation of dielectric properties of the tissues play an important part in determining the reflected and transmitted energy at interfaces between different tissue media [5].

For this reason the human head was modeled by a four-layered structure, as shown in Figure 3, consisting of skin, fat, bone and brain layer. The distance between the source and the media was elected 4.5 mm. Dielectric properties permittivity and conductivity of each layer are presented in the Table 1.

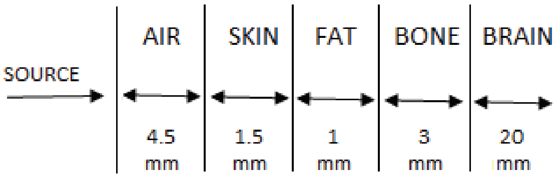

Fig.3. The geometry of the multilayered human head model

Table 1. The thickness and dielectric properties of head tissues [5]

Tissue	Thickness [mm]	Permittivity [-]	Conductivity [Sm^{-1}]
Skin	1.5	41	0.7
Fat	1	5	0.04
Bone	3	12	0.95
Brain	20	45	0.5

In order to estimate the influence of the multilayer structure composition a comparison of the EM field distribution, results for two different structures was realized. Figure 4 shows result of the distribution of electric energy density for a structure composed of skin, fat, bone and brain, compared to those given in Fig. 7 in which the structure contains a tumour placed in the part of brain. In both figures is visible a creation of subdermal hot spots caused by the raise of the energy storage in the fat layer.

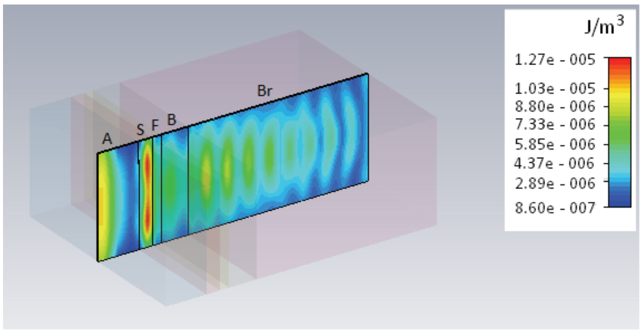

Fig.4. The distribution of electric energy density in the multilayered human head model, A – air, S – skin, F – fat, B – bone, Br - brain

Figure 5 shows the magnitude of reflection coefficient S_{11} at X-band frequency range for multilayerded human head model. It can be seen that the values of S_{11} coefficient oscillates due to the multiple reflection at the interfaces between sample layers. The magnitude of reflection coefficient S_{11} has decreasing character.

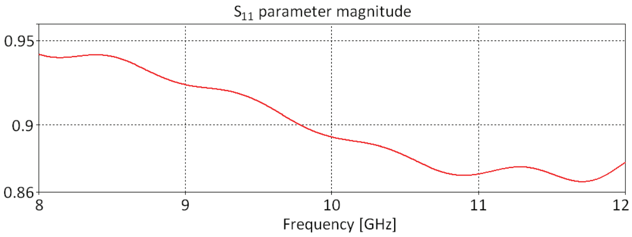

Fig.5. Reflection coefficient magnitude for multilayered human head model at X-band frequency range

Similarly, in the figure 6 there is shown the magnitude of transmission coefficient S_{21} at X-band frequency range for multilayered human head model.

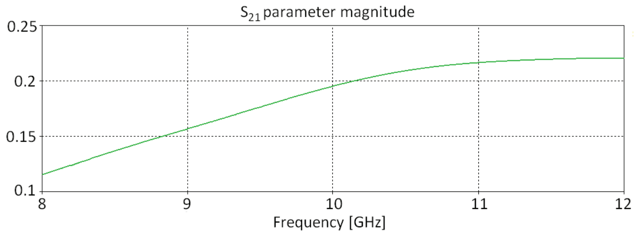

Fig.6. Transmission coefficient magnitude for multilayered human head model at X-band frequency range

The idea of next simulation was to find out the influence of tumour presence on electric energy density distribution and power loss distribution in layered biological structure. The spherical tumour with diameter 3 mm and with relative permittivity $\varepsilon' = 38$ and conductivity $\sigma = 11\ \mathrm{Sm}^{-1}$ was inserted into the brain layer under the bone layer. The electric energy density and power loss density in layered structure distribution with tumour is shown in the Fig. 7 and Fig. 8.

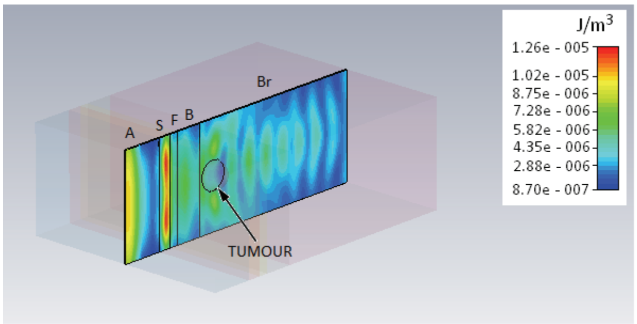

Fig.7. The distribution of electric energy density in the multilayered human head model with presence of brain tumour, A – air, S – skin, F – fat, B – bone, Br - brain

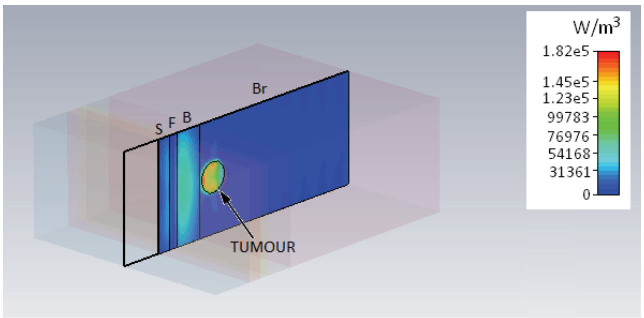

Fig.8. The distribution of power loss density in the multilayered human head model with presence of brain tumour, A – air, S – skin, F – fat, B – bone, Br - brain

In the figures is shown that the presence of tumour in the brain has a high influence on EM field distribution with result of having more field concentration than the surrounding brain layer.

Conclusion

There is the wide range of electrical properties which control the propagation, reflection, attenuation, and other behavior of electromagnetic fields in the body. These attributes depend strongly mainly on the tissue type and the frequency of interest. In this paper have been investigated the scattering properties of the multilayered structure on simplified human head model with and without the presence of a brain tumor. In the view of this analytical approach which allows us to evaluate coefficients characterizing propagation of electromagnetic wave in the layered structure, the next parameters of electromagnetic wave like SAR (specific absorption rate) or the presence of inhomogenities with different dielectric characteristic in investigated structure can be calculated.

Our results show the necessity of electromagnetic field distribution in the layered structure investigation. The experimental and numerical results connected with the study of dielectric properties of biological materials and their properties in the electromagnetic field and in the other hand the influence of dielectric properties of biological material on EM wave propagation give us the information useful at microwaves using in medical diagnostics and therapy. The presented numerical results are useful at the microwave generator parameters optimization used for microwave hyperthermia at malignant tumours treatment. This knowledge prevents the formation of undesirable regions in which arises the intensity of electromagnetic field over the safe level. The obtained numerical results can be also useful in constructing biological phantoms for dosimetry applications too.

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