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NUMERICAL MODELLING OF ELECTROMAGNETIC WAVE INTERACTON WITH HETEROGENEOUS BIOLOGICAL STRUCTURE

ING. JURAJ ZRNÍK
DOC. ING. DAGMAR FAKTOROVÁ, PHD.

Abstract: *The paper presents a numerical modeling of electromagnetic wave interaction with planar layered structure through reflection and transmission coefficient at boundaries of two biological tissues. Numerical calculation both reflection and transmission coefficients at boundaries is investigated with respect to the multiple reflections of planar electromagnetic wave at boundaries and with the respect to the transmission of reflected wave between two layers represented by fat and muscle with known dielectric properties. In our paper we presented the frequency dependence of reflection and transmission coefficient over the microwave frequency range from 1 GHz to 30 GHz and also the influence of fat layer thickness at investigated coefficients.*

Key words: *biological tissue, layered structure, reflection coefficient, transmission coefficient, microwave frequencies*

INTRODUCTION

Biological tissue is a complex and highly heterogeneous material. The results from simple models phantoms of biological tissue for microwave hyperthermia at cancer therapy 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. Boundaries between tissues with divergent dielectric properties may produce localized hot spots and cannot be ignored.

Analytical solution of a layered planar structure is given in our paper. The first problem for theoretical study of selective heating in selected layer or 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 [1-2].

1 THEORY AND MODEL OF LAYERED STRUCTURE

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 $\dot{R}$ and transmission $\dot{T}$ coefficients [3]. The transmitted wave 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.

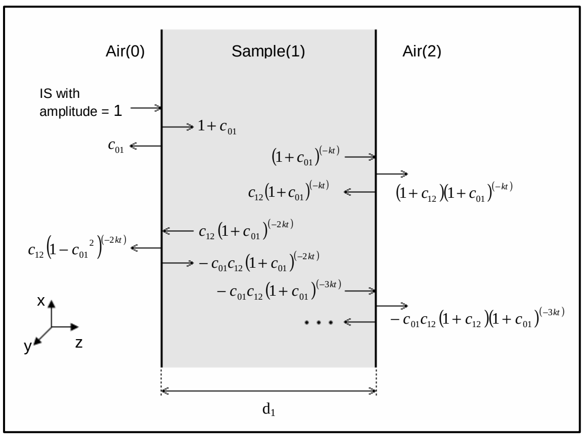

Fig.1: Single layer – multiple reflections coefficients

Fig. 1 shows the simple single-layered model. Multiple reflections are taken into consideration and the final reflection (R) and transmission (T) coefficients can be evaluated.

$$R = \frac{c_{01} + c_{12}^{(-2k_1 d_1)}}{1 + c_{12} c_{01}^{(-2k_1 d_1)}}, \tag{1}$$

$$T = \frac{(1 + c_{12})(1 + c_{01})^{(-k_1 d_1)}}{1 + c_{01} c_{12}^{(-2k_1 d_1)}}, \tag{2}$$

$$CR = \frac{c_{12}(1 + c_{01})^{(-2k_1 d_1)}}{1 + c_{01} c_{12}^{(-2k_1 d_1)}}, \tag{3}$$

$$CL = \frac{(1 + c_{01})^{(-k_1 d_1)}}{1 + c_{01} c_{12}^{(-2k_1 d_1)}}, \tag{4}$$

where *CR* represents total signal incident on the boundary *01* from the right and *CL* represents total signal incident on the boundary *12* from the left. In other words *CR* and *CL* represents total sum of multiple reflections within sample. The value *d* represents layer thickness, k_i are propagation constants of *i*-th layer (complex value) and c_{ij} are reflection coefficients from *ij* boundary.

Obviously the next step is to add one layer and thus create more complex structure. The idea is to replace two layers with an equivalent single one, Fig. 2.

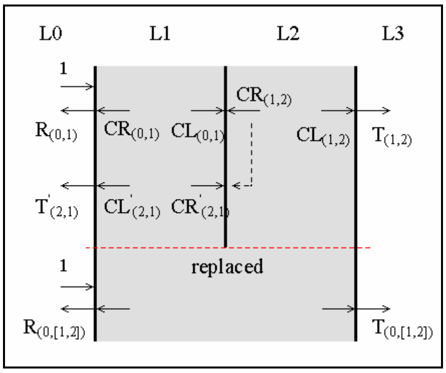

Fig.2: Two-layered model with corresponding coefficients

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 coefficients $R_{(0,[1,2])}$ and $T_{(0,[1,2])}$.

$$R_{(0,[1,2])} = R_{(0,1)} + \frac{CL_{(0,1)} CR_{(1,2)} T'_{(2,1)}}{1 - CR'_{(2,1)} CR_{(2,1)}}, \tag{5}$$

$$T_{(0,[1,2])} = \frac{CL_{(0,1)} T_{(1,2)}}{1 - CR_{(1,2)} CR'_{(2,1)}}. \tag{6}$$

This procedure can be then applied for *n*-layered structure.

In our paper we study the uniform plane wave with the electric field vector linearly polarized along the *x* axis impinging normally in *z* direction on a boundary – in our case on the chosen part of human body. First simulation represents simplest two-layered structure composed of skin and fat (subcutaneous fat) where the incident signal arrives from semi-infinite free-space and finally is transmitted into semi-infinite free-space again, Fig. 3.

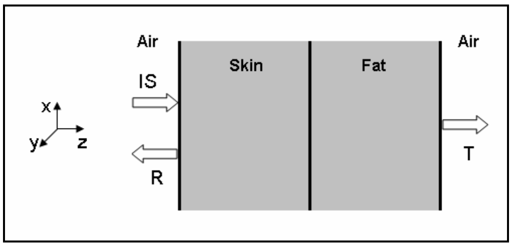

Fig.3: Two layers of dielectric materials (IS – incident signal), wave is transmitted into free space

Second simulation represents two-layered structure composed of skin and fat where the incident signal arrives from semi-infinite free-space and finally is transmitted into another tissue, Fig. 4. In this case we observe changes in transmission coefficient directly in the muscle. This can be used later by studying tissue changes like tumours and other abnormalities.

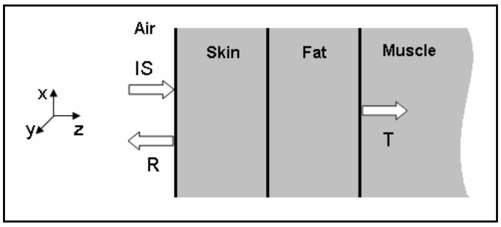

Fig.4: Two layers of dielectric materials (IS – incident signal), wave is transmitted into next tissue

Of course this mathematical model can be expanded for *n* layers.

Each tissue in organism has a different complex permittivity and reflections of electromagnetic energy occur at the various tissue interfaces. The reflected energy will be influenced not only by the wave impedance of each layer, but by the layer thickness as well. For the planar model, these effects may be derived from the standard transmission line equations. In a finite layered dielectric, multiple reflections and transmissions of electromagnetic wave occur at each boundary. The chief concern of this paper is in influence of the layer thickness and frequency on resulting signal.

2 Numerical Results

We applied cascade technique for the multiple reflections and transmissions calculation. This technique provides a calculation of the reflection coefficient $\dot{R}$ at the first boundary which includes any contributions from all the subsequent boundaries. The transmission coefficient $\dot{T}$ which corresponds to the reflection coefficient $\dot{R}$ can be obtained by applying the boundary conditions. The incident wave is assumed to have harmonic character and amplitude equal to 1. We calculated the complex reflection and transmission coefficient, due to a wave transmitted from fat to muscle layer with thickness much greater then the depth of penetration using MATLAB program based on general theory of planar dielectric layers.

The reflection and transmission coefficients are related to the return loss R and attenuation T in dB, respectively

$$r = 20\log\left|\dot{R}\right| \ , \ t = 20\log\left|\dot{T}\right| . \qquad (7)$$

Wideband solution of R and T indicate their cyclical variations with frequency due to the multiple reflections between interfaces beating in and out of phase. The peaks and troughs at frequency dependence of R and T occur when the sample thickness is a multiple of a quarter wavelengths.

In the first simulation is the structure composed of skin layer (2 mm) and fat layer which thickness changes in range 1 – 50 mm.

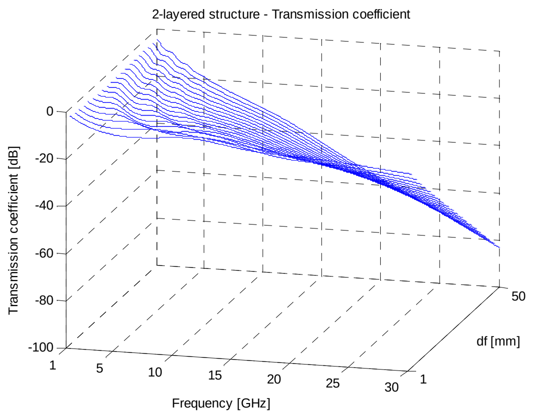

Fig.5: Transmission coefficient – two layers (ASFA = air/skin/fat/air) – change in thickness of second layer (fat)

Fig. 5 shows the variation in the magnitude of the transmission coefficient T with varying fat layer thickness d_f. The magnitude of T with increasing frequency decreases because the penetration depth of electromagnetic wave in high water content tissue – in our case fat – is $d = 0.02$ m at frequency 10 GHz and electromagnetic wave is significantly attenuated.

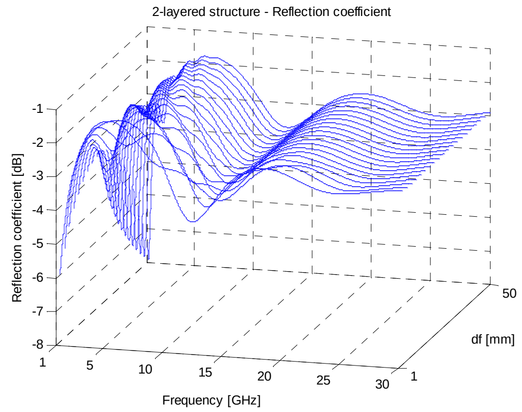

Fig.6: Reflection coefficient – two layers (ASFA) – change in thickness of second layer (fat)

Fig. 6 shows the variation in the magnitude of the reflection coefficient r with varying fat layer thickness and with frequency. It can be seen that the values of reflection coefficient highly oscillates due to the multiple reflection at the interfaces between two biological sample layers. The magnitude of oscillations decreases with increasing frequency and tends to a constant value.

The dips in the course of reflection coefficient indicate frequency interval in which power of the incident electromagnetic wave is absorbed.

In the second simulation is the structure similar to the first composed of skin layer (2 mm) and fat layer which thickness changes in range 1 – 50 mm, but the signal which is transmitted through these 2 layers arrives into another tissue (muscle).

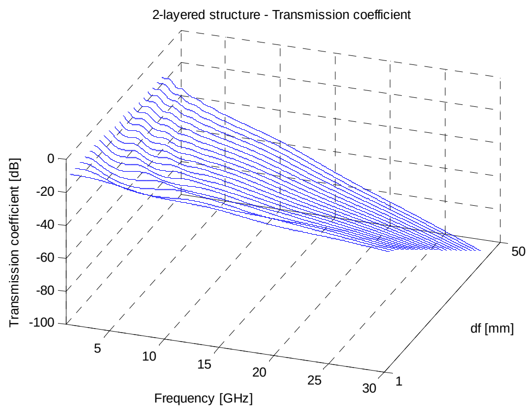

Fig.7: Transmission coefficient – two layers (ASFM) – change in thickness of second layer (fat)

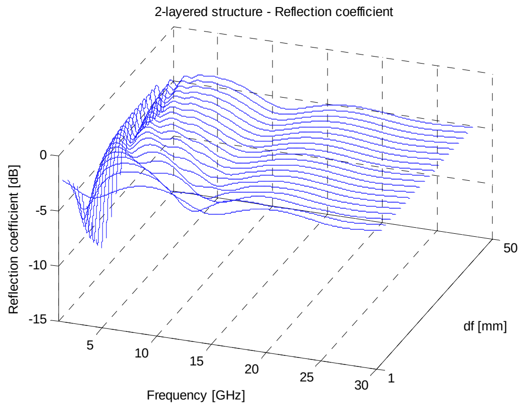

Fig.8: Reflection coefficient – two layers (ASFM) – change in thickness of second layer (fat)

The third pair of graphs represents situation similar to second simulation, but the parameters are: skin layer – change in thickness (0.5 mm – 5 mm), fat layer (constant thickness 10 mm).

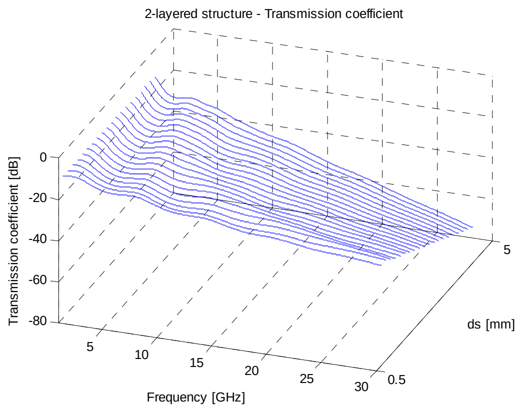

Fig.9: Transmission coefficient – two layers (ASFM) – change in thickness of first layer (skin)

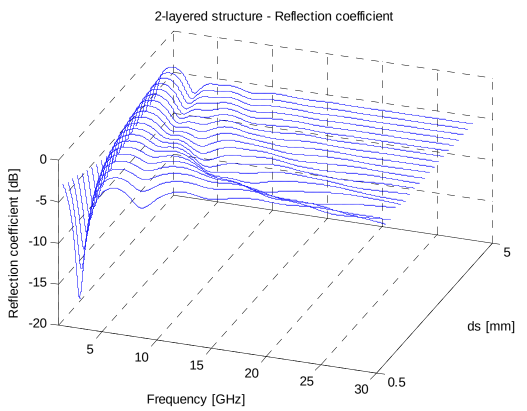

Fig.10: Reflection coefficient – two layers (ASFM) – change in thickness of first layer (skin)

3 Conclusion

The presented numerical approach enables numerical calculation of both reflection and transmission coefficients in any number, combination and thickness of biological tissues at chosen frequency interval. The presented results are useful also at the microwave generator parameters optimization used for microwave hyperthermia at malignant tumours treatment. The obtained numerical results can be useful also at design of chosen human body part phantoms.

In the wiev of this analytical approach which allows us to evaluate coefficients characterizing propagation of electromagnetic wave in the layered structure, the next parameters of EM wave like SAR, or the presence of inhomogenities with different dielectric characteristic in investigated structure can be calculated.

This model is concentrated on influence of thickness change and permittivity values used in simulation were constant (for frequency 10 GHz). Therefore the next work will be focused on observing frequency dependence of permittivity and on signal incident under different angles.

4 Acknowledgement

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Juraj Zrník, Ing.
Dagmar Faktorová, Doc., Ing., PhD.
DMAEE, Faculty of Electrical Engineering
University of Žilina
Univerzitná 8215/1, 010 26 Žilina, Slovak Republic
e-mail: zrnik@fel.uniza.sk, faktor@fel.uniza.sk