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Calculation of the Coaxial-Slot Antenna Characteristics used for the Interstitial Microwave Hyperthermia Treatment

***Abstract**. The coaxial-slot antennas are commonly used during the interstitial microwave hyperthermia treatment due to their simplicity and high efficiency of tissue heating. This article presents the numerical estimation of the antenna impedance, the reflection coefficient and antenna radiation patterns in near- and far-field as a function of frequency for the microwave antenna with a 50 Ω coaxial feed. Axial symmetry allows the modelling of this problem using TM electromagnetic wave coupled with the Pennes bioheat transfer equation. For the numerical implementation the finite element method has been used and the simulations have been carried out within the various tissues for the antenna operating frequency of 2.45 GHz.*

Streszczenie**. Anteny współosiowe ze szczeliną powietrzną są powszechnie stosowane w czasie leczenia śródmiąższową hipertermią mikrofalową ze względu na ich prostotę i wysoką efektywność w grzaniu tkanek. Niniejszy artykuł przedstawia numeryczne szacowanie impedancji anteny, współczynnika odbicia oraz charakterystyk promieniowania anteny w polu bliskim i dalekim, jako funkcje częstotliwości dla anteny mikrofalowej z 50 Ω zasilaniem koncentrycznym. Symetria osiowa pozwala na modelowanie problemu przy użyciu elektromagnetycznej fali TM sprzężonej z biologicznym równaniem przepływu ciepła Pennesa. Do realizacji numerycznej wykorzystano metodę elementów skończonych a symulacje przeprowadzono wewnątrz różnych tkanek dla częstotliwości pracy anteny 2.45 GHz.* (Wyznaczanie charakterystyk współosiowej anteny ze szczeliną powietrzną używanej do leczenia śródmiąższową hipertermią mikrofalową***)

Keywords: interstitial microwave hyperthermia, coaxial-slot antenna, antenna impedance, reflection coefficient, antenna radiation patterns
Słowa kluczowe: śródmiąższowa hipertermia mikrofalowa, antena współosiowa ze szczeliną powietrzną, impedancja anteny, współczynnik odbicia, charakterystyki promieniowania anteny

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Introduction

In the modern world, people are struggling with ubiquity of electromagnetic fields, and like it or not they are exposed to their beneficial or negative effects. High-frequency fields (for example, produced by mobile phones) are considered to be potentially dangerous because prolonged exposure to such fields can lead to the overheating of the body parts in their direct proximity (head in the case of mobile phone users) [1]. However, electromagnetic fields are also increasingly used in medicine both for therapeutic and diagnostic purposes. A good example may be a magneto-therapy in the case of low-frequency fields [2] as well as thermal therapy in the case of high-frequency fields. The microwave interstitial hyperthermia described in this paper is a minimally invasive method for the treatment of pathological cells located deep in the body [3]. This special thermal technique has found particular applications in the treatment of cancer, because it allows the heating of tumors, minimally affecting the surrounding healthy tissues. The study showed that the high temperature in the range of $40 - 45^{\circ}\mathrm{C}$ may lead to necrosis of the cells within a distance of $1 - 2$ cm from the heat source [4]. Recently a parallel method involving of hyperthermia using magnetic nanoparticles for the treatment of cancer is still developed [5].

Technological development observed in recent years has resulted in various types of antennas for thermal therapy. The presented coaxial-slot antenna for the microwave interstitial hyperthermia belongs to the kind of feed antennas and aperture antennas [6]. The interstitial applicator typically consists of the feeding coaxial cable with alternating layers of conductor and dielectric. The air gap is usually placed inside surrounding metal surfaces. To describe the antenna's performance it is sufficient to specify the radiation pattern characteristics, the input impedance and the reflection coefficient at the defined feed point [7].

This paper presents the basic characteristics of microwave coaxial-slot antenna having the best antenna matching and the required level of temperature in the treated tissue. In order to better model validation the obtained results are compared for several tissues typically treated during interstitial hyperthermia treatment, namely breast, brain, kidney, liver and lung tissues [8].

Geometry and Govern Equations

The geometry of the microwave antenna comprises central conductor (with radius of 0.135 mm), dielectric (0.470 mm), outer conductor (0.595 mm) and a protective catheter (0.895 mm, see Fig. 1). The entrance of the dielectric has the coaxial feed with the $50\ \Omega$ impedance. What is important, in the outer conductor there is an air gap with a width $d = 1$ mm by which electromagnetic waves is radiated into the tissue. The model takes advantages of the rotational symmetry of the problem, which allows the 2D modelling using cylindrical coordinates (r, ϕ, z).

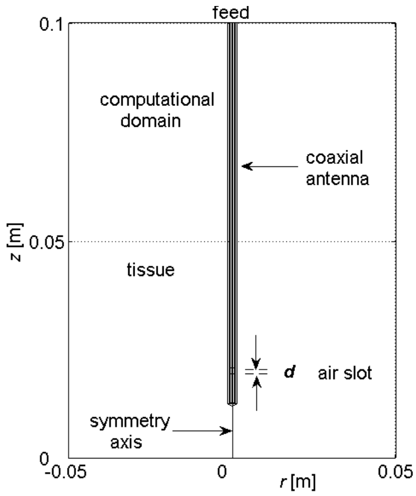


Fig.1. The 2D model of the coaxial-slot antenna placed in the tissue

Since the presented model is axis-symmetric, transverse magnetic (TM) waves are used and there are no electric field variations in the ϕ -direction. A magnetic field strength has only the tangential component $\mathbf{H} = H_{\phi}\,\mathbf{e}_{\phi}$ and an electric field strength propagates in the r-z plane $\mathbf{E} = E_r = \mathbf{e}_r + E_z\,\mathbf{e}_z$. Considering the above, the following wave equation with respect to the magnetic field strength should be resolved

$$\nabla \times \left[\left(\varepsilon_{\mathrm{r}} - \mathrm{j}\frac{\sigma}{\varepsilon_0 \omega} \right)^{-1} \nabla \times H_{\phi} \right] - \varepsilon_0 \mu_0 \mu_{\mathrm{r}} \omega^2 H_{\phi} = 0 \tag{1}$$

where ε_0 and μ_0 are properly the electric and magnetic constants, and ε_r and μ_r are the relative permittivity and relative permeability of the medium, respectively. Moreover, σ is the electrical conductivity of the body, ω is the angular frequency of the EM field and j is the imaginary unit. What is important, the seed point is modelled using a port at the entrance of dielectric with the power level set to P_{in}. The full description of all boundary conditions used in the present simulation can be found in [8].

The axial-symmetrical wave equation is coupled with the Pennes bioheat transfer equation [9] defined by

$$\nabla\left(-k\nabla T\right)=\rho_b C_b \omega_b (T_b-T)+Q_{ext}+Q_{met} \tag{2}$$

where T denotes the body temperature (K), k – the tissue thermal conductivity (W m^{-2} K^{-1}), T_b – the blood vessel temperature (K), ρ_b – the blood density (kg m^{-3}), C_b – the blood specific heat (J kg^{-1} K^{-1}), ω_b – the blood perfusion rate (s^{-1}). The model also takes into account the so-called the metabolic heat generation Q_{met} (W m^{-3}) as well as the external heat sources $Q_{ext} = 0.5\,\sigma\,|\mathbf{E}|^2$ (W m^{-3}).

The antenna efficiency depends mainly on the antenna reflection coefficient Γ, which determines the losses associated with the attenuation of the reflected wave at port. In the logarithmic measure it has been defined as [7]:

$$S_{11}=20\log_{10}\left(|\Gamma|\right)=20\log_{10}\sqrt{\frac{P_r}{P_{in}}}\ [\mathrm{dB}] \tag{3}$$

where P_{in} denotes the total antenna power incident on port and P_r the total antenna power reflected from port. Knowing the Γ parameter, the antenna impedance seen from of the antenna input terminal can be determined according to [10]:

$$Z_{in}=Z_c\frac{1+\Gamma}{1-\Gamma} \tag{4}$$

where Z_c = 50 Ω is the characteristic impedance of coaxial cable. The radiation pattern of the microwave antenna in the near-field is obtained from the expression

$$P_{db}=10\log_{10}\left(P_{out\ flow}\right)\ [\mathrm{dB}] \tag{5}$$

where $P_{out\ flow}$ denotes the amount of power flowing out from the port given by the normal component of the Poynting vector $\mathbf{S}$, namely

$$P_{out\ flow}=\mathbf{n}\cdot\mathbf{S}=0.5\,\mathbf{n}\cdot\mathrm{Re}(\mathbf{E}\times\mathbf{H}^*) \tag{6}$$

The electromagnetic field in the far-field of the coaxial-slot antenna (measured at infinity) can be determined on the basis of near-field one using a Stratton-Chu formula [10]:

$$\mathbf{E}_{far}=\frac{jk_0}{4\pi}\mathbf{n}\times\int\left[\mathbf{n}\times\mathbf{E}-Z_0\,\mathbf{n}\times\left(\mathbf{n}\times\mathbf{H}\right)\right]e^{jk_0\mathbf{r}\cdot\mathbf{n}}dS \tag{7}$$

where S is a sphere surface surrounding the antenna with radius $\mathbf{r}$, $\mathbf{n}$ – the unit vector perpendicular normal to the surface S. Moreover, $Z_0 = 377$ Ω denotes the wave impedance in vacuum, and $k_0 = \omega\sqrt{(\varepsilon_0\ \mu_0)}$ is a free-space wave number. Since the far-field is defined in a vacuum, therefore the magnetic field in the far-field is given by

$$\mathbf{H}_{far}=\frac{\mathbf{n}\times\mathbf{E}_{far}}{Z_0} \tag{8}$$

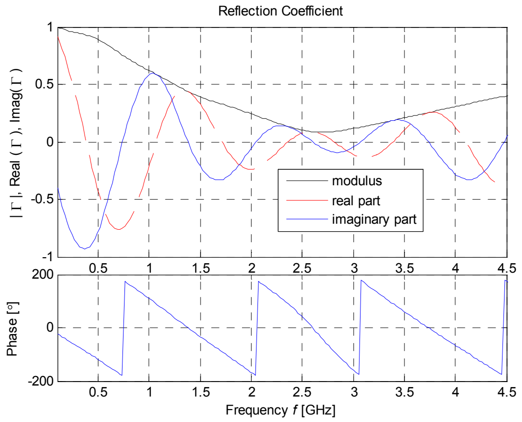
and the Poynting vector describing the power flow in the far-field is governed by:

$$P_{far}=\mathbf{n}\cdot\mathbf{S}_{far}=0.5\,\mathbf{n}\cdot\mathrm{Re}(\mathbf{E}_{far}\times\mathbf{H}^*_{far})\sim\left|\mathbf{E}_{far}\right|^2 \tag{9}$$

Govern equations given above (1) – (9) were solved using the finite element method.

Simulation Results

The dimensions of the antenna and its material constants have been taken from the literature [7]. It was assumed that the antenna operates at the working frequency of f_o = 2.45 GHz, and the antenna input power at the feed point is fixed at P_{in} = 1W, which ensures that the temperature in the human tissues does not exceed 45°C. It has been also assumed that the human tissues and microwave antenna are considered as uniform mediums with constant material parameters. The electro-thermal parameters for different tissues at the adopted antenna operating frequency are the same as in ITIS date base [11]. All calculated results have been summarized in the following Figures 2 – 4. The antenna reflection coefficient Γ and the antenna input impedance Z_{in} at the port as a function of frequency within the human liver tissue are shown in Fig. 2. What is important, the real and imaginary parts of Γ are shifted and the magnitude of Γ represents the envelope for these functions. Next Fig. 3 demonstrates zoomed plots for similar quantities and various human tissues as a function of normalized frequency. This time, the reflection coefficient is expressed in decibel scale through the S_{11} parameter. The magnitude of the antenna impedance (in wide frequency range) fluctuates around the value of 50 Ω, which corresponds to the characteristic impedance of a coaxial feed and ensures maximum transmission to the vacuum. Moreover, the near-field and far-field radiation patterns as a function of the antenna elevation angle within various tissues have been gathered together in Fig.4.



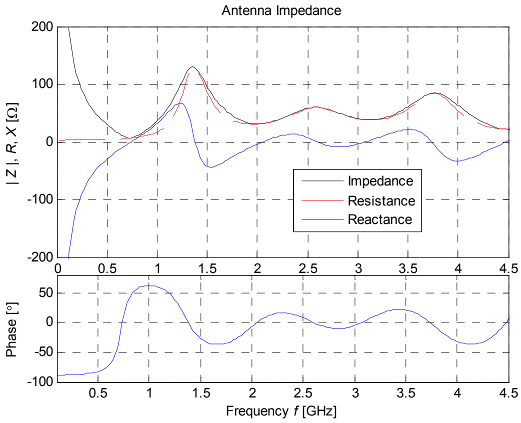


Fig.2. The antenna reflection coefficient (left) and the antenna impedance (right) versus frequency for the liver tissue with indication of their modulus, real and imaginary parts as well as phase angle

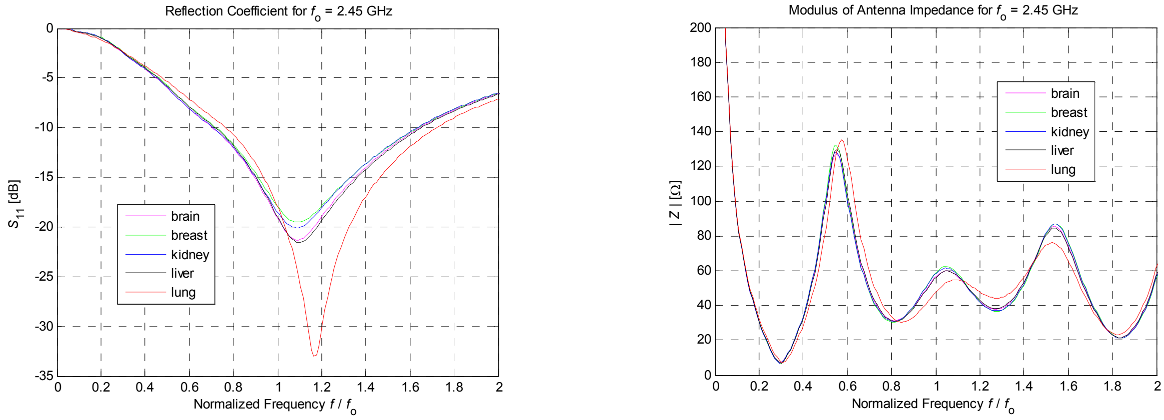


Fig.3. The S_{11} parameter (left) and modulus of the antenna impedance (right) and the as a function of the normalized frequency within different tissues for the antenna operating frequency $f_o = 2.45$ GHz

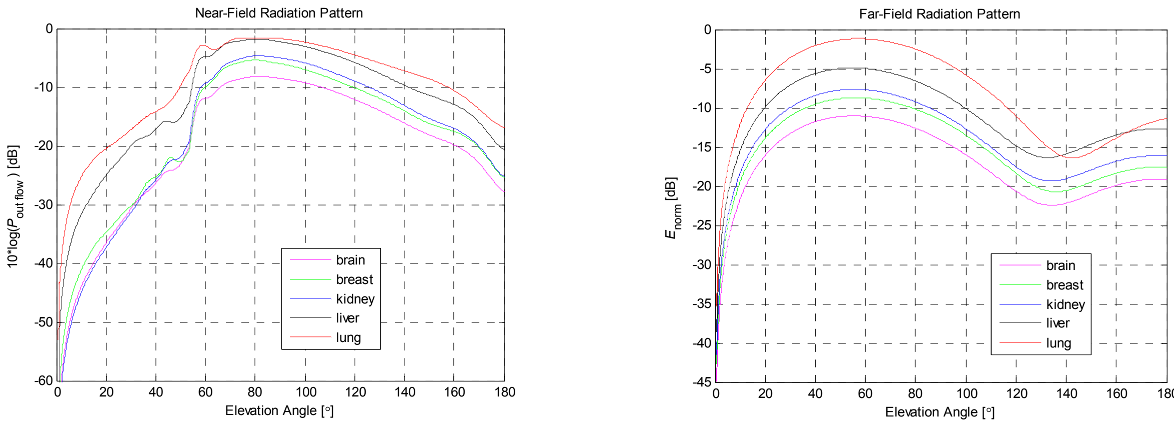


Fig.4. The microwave coaxial-slot antenna radiation pattern in the near-field (left) and in the far-field (right) as a function of the elevation angle within various tissues for the antenna operating frequency $f_o = 2.45$ GHz

Summary

In the presented paper the main microwave coaxial-slot antenna characteristics have been investigated and compared for several tissues typically treated during interstitial hyperthermia treatment. In the case of the liver tissue and the antenna operating frequency $f_o = 2.45$ GHz the real and imaginary parts of the reflection coefficient have values 0.0564 and 0.0972, respectively. The smallest amplitude of Γ (the best antenna matching and power transmission to the tissue) occurs at the frequency of 2.68 GHz. It corresponds to the value in the decibel scale of about -21.55 dB. The phase angle for this parameter is equal to zero at 2.60 GHz. Moreover, for the breast and kidney tissues as well as the brain and liver tissues the minimum values of the S_{11} parameter are properly as follows -19.54 dB, -20.54 dB, -21.29 dB and -21.55 dB, while the lung tissue has much better antenna matching with S_{11} at the level of -33.02 dB for the frequency of 2.85 GHz. A similar trend is clearly visible for the modulus of the antenna impedance. For the lung tissue, the antenna impedance at the antenna operating frequency is about $47.4\ \Omega$ while for other tissues it has value from the range $60 - 62\ \Omega$. What is more, the radiation patterns in the near-field and far-field of the antenna adopt the highest level in the case of the liver tissue, and lower and lower levels for the liver, kidney, breast tissues, respectively, and the lowest level of the brain tissue. The presented simulations confirm the theory.

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