Applicator for Superficial Microwave Hyperthermia Filled with Anisotropic Dielectric Media: Numerical Investigation of Design Degrees of Freedom

J. Vrba, Jr.[1], **D. Vrba**[1], **M. Wiewegh**[1], **and J. Vrba**[2]

[1]Faculty of Biomedical Engineering, Czech Technical University in Prague, Czech Republic
[2]Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic

Abstract— In this paper properties of an rectangular-waveguide applicator (test applicator) for superficial microwave hyperthermia filled with stratified isotropic and/or anisotropic dielectric media are discussed. Man-made biaxial anisotropic material is considered here. Electric field distributions in a cross-section of the test applicator filled with anisotropic material are compared with the test applicator filled completely with water and with the one partially filled with water and partially with high permittivity materials. Furthermore, for some applicators power loss densities in the virtual phantom of muscle tissue are numerically estimated.

1. INTRODUCTION

From all applicators for superficial microwave hyperthermia proposed in the past and used now in the field of RF/microwave hyperthermia rectangular-waveguide applicators excels, in comparison to planar applicators, in

1. homogeneity of the SAR distribution created in the treated biological tissue,
2. low leaked electromagnetic fields, due to closed metallic walls around the applicator aperture.

On the other hand, the main drawbacks of these applicators are that they are fairly bulky and heavy. Often, in order to decrease the dimensions of these applicators/decrease their working frequency they are completely filled with water that makes them even weightier.

In the past the effective aperture of the rectangular-waveguide applicator with TE_{10} mode was improved using side dielectric slabs of titanium dioxide which shows high relative electric permittivity. The rest of these modified applicators is filled with water.

The numerical investigation performed and presented in this paper is motivated by expectation that by filling a rectangular waveguide with anisotropic media the number of degrees of freedom for the applicator design will increase. The parameters like power loss distribution produced in the treated area as well as electric field distribution in the applicator cross-section are the main investigated properties in this paper.

The proposed rectangular-waveguide applicator is compared with a rectangular waveguide applicator filled completely with water and with the one partially filled with water and partially with titanium dioxide slabs.

The numerical simulations are performed using a full-wave well-proven commercial electromagnetic field simulator COMSOL Multiphysics [1].

2. BIAXIAL DIELECTRIC MATERIAL

In the presented analysis the problem is considered to be loss-less and the anisotropic dielectric material is a composite of two materials. The material which forms a continuous phase is loss-less and shows permittivity ε_c. The other material is considered as perfect electric conductor (PEC) and it is dispersed in the continuous phase in a form of mono-spheres (all spheres have the same radius r) in a rectangular lattice with lattice parameters a_x, a_y and a_z in x-, y- and z-direction. The considered anisotropic material has lattice parameters $a_x = a_z \neq a_y$, which in crystallography corresponds to tetragonal $a_x = a_z \neq a_y$ crystal system). Such material belongs to a class of so called biaxial [2] materials. This means that the permittivity can be written in a Cartesian coordinates as diagonal matrix and permittivity in x- and z-directions have to be the same

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_x \end{pmatrix}.$$

Design of the anisotropic material is not the goal of the presented study. The geometry of such material is in Fig. 1.

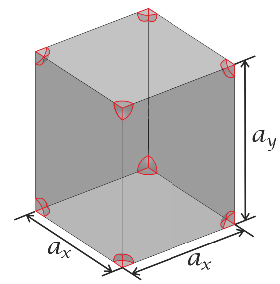

Figure 1: 3D view of a unit cell with 1 sphere of radius r. The is geometry periodical with a spatial period in all three dimensions equal to the corresponding unit cell edge length a_x, a_y and a_z.

3. FIELD DISTRIBUTION INSIDE APPLICATORS FILLED WITH ISOTROPIC MATERIAL

The geometries of rectangular waveguides considered here are depicted in Fig. 2. For the rectangular waveguide filled completely with an isotropic material, in this case water, the dominant mode is TE_{10} [3].

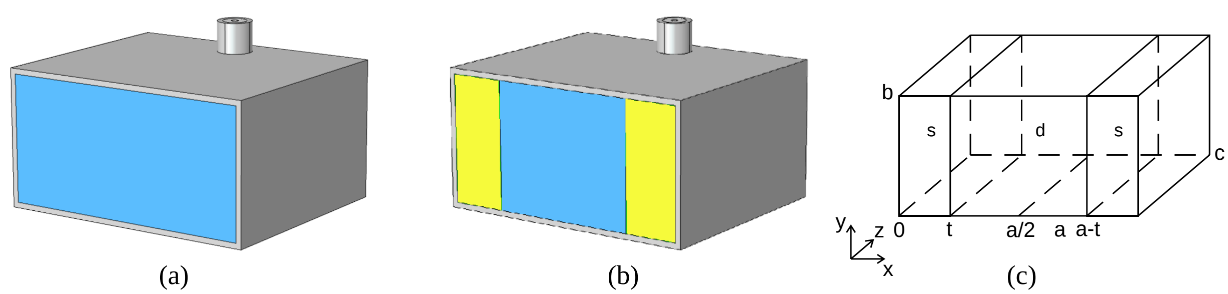

Figure 2: Geometries of the considered rectangular-waveguide applicators: (a) applicator completely filled with water (depicted in blue), (b) applicator partially filled with dielectric isotropic/anisotropic material (depicted in yellow). (c) Rectangular waveguide dimensions and orientation. $a = 70\,\mathrm{mm}$, $b = 35\,\mathrm{mm}$ and $c = 60\,\mathrm{mm}$. Thickeness of the slabs is denoted as t.

The dominant mode of the rectangular-waveguide applicator filled with stratified media as depicted in Fig. 2 is a slightly modified TE_{10}. Basic properties of the rectangular waveguide filled with three layers of isotropic material, e.g., cut-off frequency of the dominant mode, phase constant in propagation direction β_z, EM field distribution, were evaluated using a well-known theory [4]. One of the steps necessary to evaluate the basic properties is to numerically solve following transcendental equation

$$\begin{aligned} &\left(\omega^2\varepsilon_d\mu-\beta_z^2\right)\sqrt{\omega^2\varepsilon_s\mu-\beta_z^2}\tan\left(\sqrt{\omega^2\varepsilon_s\mu-\beta_z^2}t\right) \\ =\ &\left(\omega^2\varepsilon_s\mu-\beta_z^2\right)\sqrt{\omega^2\varepsilon_d\mu-\beta_z^2}\cot\left(\sqrt{\omega^2\varepsilon_d\mu-\beta_z^2}\left(\frac{a}{2}-t\right)\right), \end{aligned} \tag{1}$$

where ε_d, ε_s are permittivity of inner region and slabs, respectively. The ability of an applicator to homogeneously irradiate the treated area can be estimated by computation of power loss density. Biological tissues show negligible magnetic loss and for homogeneous phantom considered here the power loss density is proportional to $|E|^2$. The field distribution in the waveguide will be plotted for the dominant electric field component E_y.

4. NUMERICAL MODEL

The numerical model is based on a simple rectangular waveguide applicator feeded with a coaxial port.

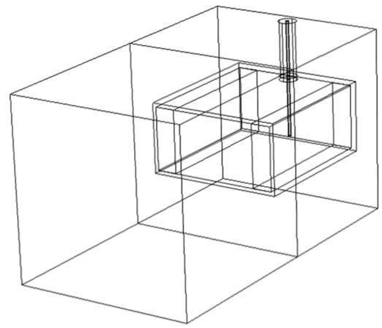

Figure 3: Numerical model of the applicator virtually irradiating a muscle tissue phantom.

It is basically an adapter between coaxial and rectangular waveguide technology where the rectangular waveguide aperture lay on a patient to be treated (mostly there is a water bolus between patient and the applicator, the water bolus is for simplicity omitted here). In this numerical model the tested applicator virtually irradiates phantom of a muscle tissue. Dielectric properties of muscle tissue at the working frequency can be found in [5].

5. RESULTS

Field distribution $|E_y|^2$ of the dominant TE_{10} mode in the rectangular waveguide filled with homogeneous (Fig. 2(a) [4]) and stratified isotropic media (for modified TE_{10} mode, Figs. 2(b) and (c) [4] and Eq. (1)) has been found, respectively and they are plotted in Fig. 4.

Relative permittivity of water and TiO_2 in the evaluated field distribution is consider 80.1 and 100, respectively. For an microwave applicator, effective treatment is considered in a region of treated patient, where power loss density induced with the applicator falls to 50% of its maximum. This region is proportional to the length ℓ of an aperture in x-direction plotted in Fig. 4. For two combinations of permittivities (water/TiO_2 and water/$\varepsilon_r = 300$) field distribution was optimized by varying thickness t of the slabs. Two 2.9 cm thick TiO_2 slabs improve the homogeneity of the

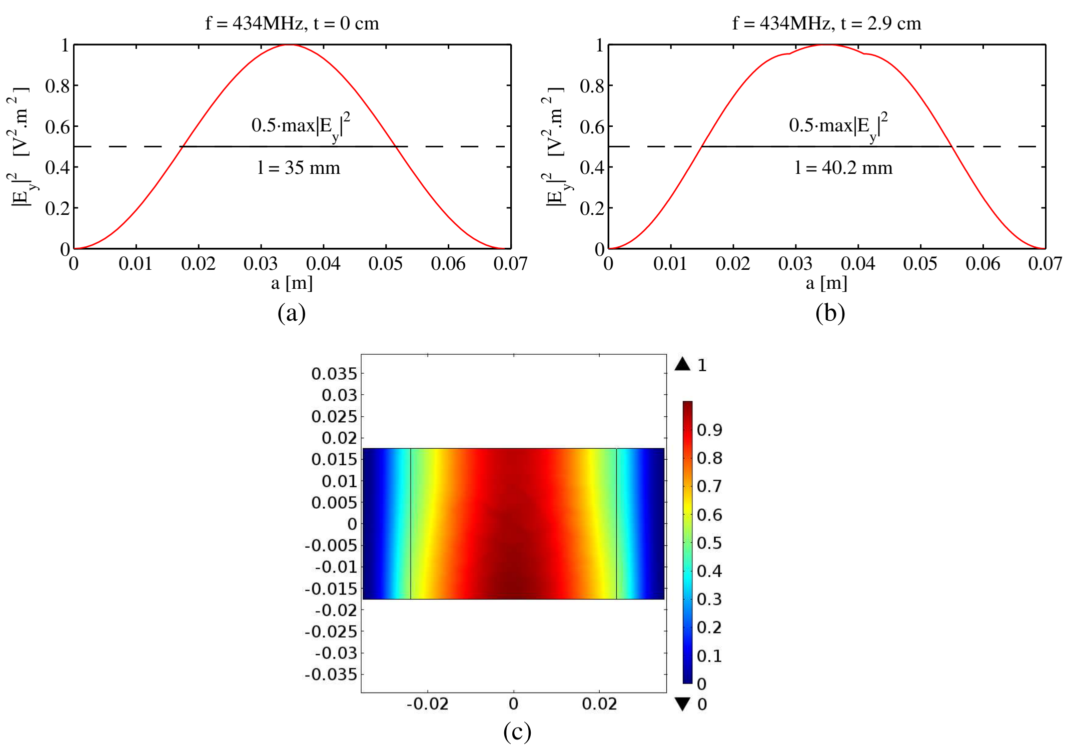

Figure 4: (a) Electric field distribution $|E_y|^2$ in rectangular waveguide filled with water only, (b) partially with water and partially with TiO_2 and (c) partially with water and partially with an isotropic material with $\varepsilon_r = 300$.

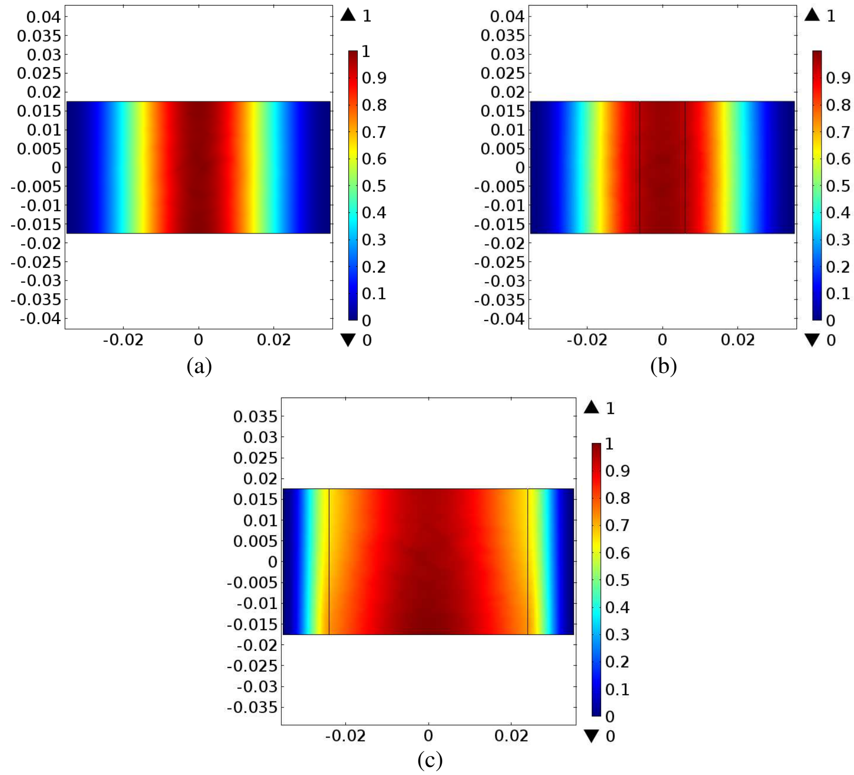

Figure 5: (a) Electric field distribution $|E_y|^2$ in rectangular waveguide filled with water only, (b) partially with water and partially with TiO_2 and (c) partially with water and partially with an isotropic material with $\varepsilon_r = 300$.

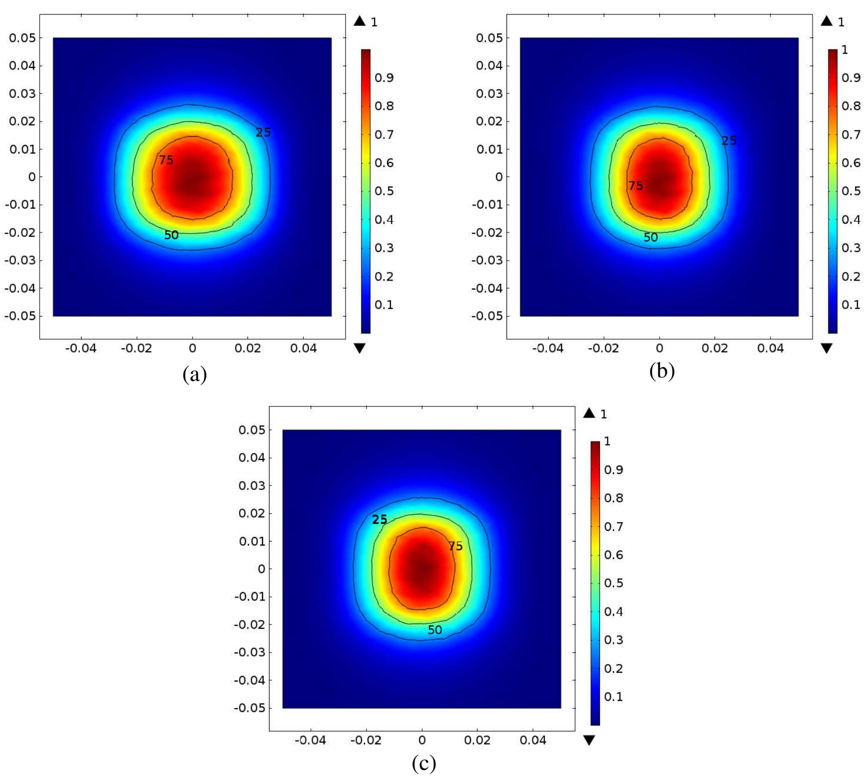

Figure 6: (a) Power loss distribution (1 cm bellow the surface of the phantom) produced by the rectangular waveguide applicator filled partially with water and partially with an isotropic material with $\varepsilon_r = 300$ and (b) by the rectangular waveguide filled partially with water and partially with an anisotropic material with $\varepsilon_{rx} = \varepsilon_{rz} = 300$ and $\varepsilon_{ry} = 80$. (c) By the rectangular waveguide filled partially with water and partially with an anisotropic material with $\varepsilon_{rx} = 300$ and $\varepsilon_{ry} = \varepsilon_{rz} = 80$.

field distribution in the waveguide cross-section by a factor of $A = 40.2/35 = 1.15$ (relative to homogeneously filed applicator). Using high-permittivity ($\varepsilon_r = 300$) dielectric slabs with slabs of $t = 1.1$ cm yields $A = 1.62$. There is a danger of excitation of higher-order modes (excitation of higher order modes is tested numerically). in this paper the possibility to suppress higher-order modes using anisotropic materials is investigated.

In Fig. 5 numerically estimated electric field distribution $|E_y|^2$ in rectangular waveguides filled with water only (a), partially with water and partially with TiO_2 (b) and partially with water and partially with an isotropic material with $\varepsilon_r = 300$ (c) are plotted. For the last case the field distribution shows certain dependency in y-direction. This dependency in y-direction may degrade ability of the applicator homogeneously irradiate a treated area.

If the permittivity of slabs was considered anisotropic (analysis was performed for following cases $\varepsilon_{rx} = \varepsilon_{rz} = 300$ and $\varepsilon_{ry} = 80$, $\varepsilon_{rx} = \varepsilon_{rz} = 300$ and $\varepsilon_{ry} = 250$, $\varepsilon_{rx} = 300$ and $\varepsilon_{ry} = \varepsilon_{rz} = 80$) the numerically estimated field distribution in the applicator cross-section showed narrower pattern than for the applicator with slabs of isotropic material with $\varepsilon_r = 300$. Instead of plotting the field distributions we have decided to plot power loss densities produced by applicators 1 cm under the surface of the phantom. Numerically estimated power loss density produced by applicators filled with isotropic and anisotropic slabs is plotted in Figs. 6(a) and (b), (c), respectively. Again, the power loss densities for the applicator with anisotropic materials (b), (c) show narrower pattern than the applicator with isotropic materials.

6. CONCLUSIONS

Evaluated field distribution fits very well the one numerically estimated using COMSOL Multiphysics. Homogeneity of field distribution was expected to be further improved using anisotropic materials but this has not been proven in this study.

ACKNOWLEDGMENT

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