Applicators for Local Microwave Hyperthermia Based on Metamaterial Technology

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***Abstract*—In this paper we would like to demonstrate that a principle based on zero-order resonant (ZOR) metamaterial (MTM) structure can be used for the development of a novel class of applicators for microwave thermotherapy - e.g. for hyperthermia in cancer treatment or for physiotherapy. The main idea of creating such an applicator is to generate and radiate a plane electromagnetic (EM) wave into the treated biological tissue, at least in a certain extent. The main aim of this paper is to investigate, whether an EM wave generated by an MTM ZOR structure and emitted into the biological tissue can produce a homogeneous SAR distribution in the planes parallel to the applicator aperture . Electromagnetic field inside a virtual phantom of the treated region generated by the applicator that is based on the proposed MTM ZOR principle, is investigated using a well-proven full-wave commercial simulation tool.**

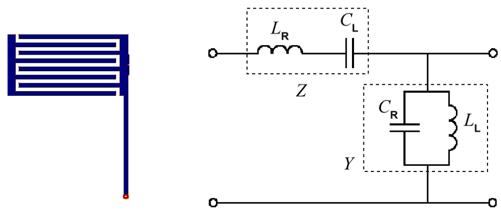
***Index Terms*—Metamaterial applicator, microwave hyperthermia, plane wave, theoretical limit of penetration depth**

I. Introduction

The main aim of this paper is to verify whether it is feasible to apply principles of MTM radiating structures in the fabrication of efficient applicators for microwave thermotherapy, especially for hyperthermia cancer treatment and for physiotherapy. For this aim, MTM antennas inspired by those described in [1], [2] will be investigated as well as adapted with respect to the requirements of effective hyperthermia treatment. In order to achieve an optimal waveform shape of the radiated EM wave, applicators have to be designed in a certain way. The best possible results can be obtained by comparing various shapes of waveforms of EM waves for local and deep local treatment waveform of plane wave., This can ensure:

- The best possible value of the effective treatment depth.
- The best possible homogeneity of SAR 3D distribution (i.e. its distribution on the surface and in the whole volume of the area to be treated).

SAR inside the virtual phantom of the treated region, created using the proposed applicator is investigated using the well-proven full-wave commercial simulation tool COMSOL Multiphysics. Based on our previous experience [1]–[3], an excellent agreement between simulation and measurement results can be expected. That is why the conclusions made in this paper are based on the results of numerical simulations only. Experimental verifications of these conclusions will be presented in the near future in following papers.



(a) (b)

Figure 1. a) Infinitesimal element of MTM b) and its equivalent circuit consisting of inherent series inductor L_R, shunt capacitor C_R, artificially inserted series capacitor C_L and shunt inductor L_L.

II. MTM zeroth order mode resonator

The concept of MTM phenomenon was first comprehensively introduced by Veselago in 1968 [4]. In the aforementioned publication, he speculated on the existence of materials whose permittivity(ϵ) and permeability(μ) were simultaneously negative. He named these materials left-handed (LH), as the $\mathbf{E}, \mathbf{H}$ and $\mathbf{k}$ vectors of the studied EM wave formed a left-handed triad if the wave propagated through such environment. The first experimental verification of MTM phenomena was performed by a research group at the University of California, San Diego (UCSD), in 2001 [5].

An infinitesimally short lossless transmission line (TL) section can be described by a simple equivalent circuit consisting of a series inductor L_R and a shunt capacitor C_R [6]. The lossless MTM cell implemented in planar technology consists of a TL section with artificially inserted series capacitorsC_L and shunt inductors L_L (with subscript L denoting its left-handed properties). The equivalent circuit of the MTM cell can be then represented by four-lumped elements (as shown in Figure 1).

Several different EM radiating structures based on the MTM principle were introduced in the past [7], [8]. Since the very beginning of the development, however, real implementation possibilities of such antennas, e.g. in communication technology, have been very limited because of their poor radiation efficiency. MTM antennas with very good radiation efficiency were first presented in [1], [2].

III. Design of the MTM zero order mode resonator technology based applicator

In this section, we will study the possibility to create MTM based applicators for local microwave hyperthermia cancer

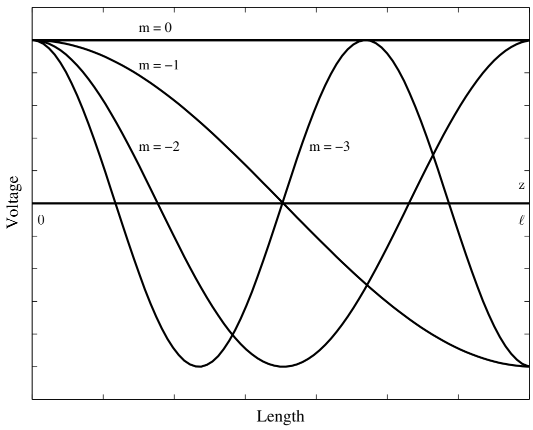


Figure 2. Voltage distribution in case of open-circuited TL of length ℓ. Mode $m = 0$ represents the ZOR with infinite guided wavelength.

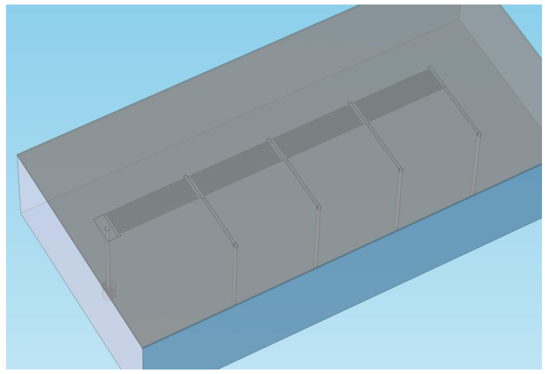


Figure 3. Example of the MTM ZOR applicator consisting of a four unit cell.

treatment at a frequency of 434 MHz. The basic part of the proposed applicator will consist of the so called zeroth order mode resonator (ZOR).

The working idea of ZOR is based on a special case of resonance that can occur when the TL meets the conditions of the MTM phenomenon. The phase constant $\beta = 0$ is at working frequency in this case, which implies infinite guided wavelength$\lambda_g = 2\pi/ \mid \beta \mid$ along the MTM structure as well as zero phase shift ($\theta_m = -\beta l = 0$) [9]. It is very important to note that this phenomenon enables creation of a very special kind of resonator whose physical length is completely independent of the classical resonance condition (i.e. required to be a natural number multiple of the half working wavelength in case of either open-circuited or short-circuited TL) [9]. The typical voltage wave distribution along the resonant length for the negative ($m < 0$) and zero ($m = 0$) resonances is shown in Figure 2. In the case of zeroth order mode resonance ($m = 0$), the value of the voltage along the ZOR is constant. A more comprehensive description of ZOR properties can be found in [9].

The working idea of an MTM ZOR applicator is that the ZOR resonant frequency should correspond to the selected working frequency. It should be noted, however, that it is possible to apply the ideas and principles of MTM applicator design described here to any selected working frequency. The initial idea of the mechanical and EM arrangements of the MTM ZOR applicator proposed here is displayed in Figure 3. As mentioned above, the working idea of an MTM ZOR applicator is that the ZOR resonant frequency should correspond to the selected working frequency. In order to obtain high radiation efficiency and thus the best possible transfer of EM energy to the treated area, we can use the main ideas, experiences, contributions and conclusions described in [1]–[3]. That means to combine the MTM ZOR structure with relatively long inductive elements along which electric current with equal phase will flow. These currents will then excite an EM wave propagating to the area to be treated. Optimal choice of positions of these inductive elements then enables us to approximate the preferred waveform . This will enable us to approximate the possible shape as well as the dimensions of the treated area. For the above mentioned main aim, some results and experiences obtained by applicators described in [10]–[13] can be used.

The working principle of this structure is the same as in [1]. Thanks to the excitation of zeroth order mode vectors of surface current density in all vertical parts of the antenna, all these surface currents are in phase, i.e. the radiated contributions from all individual vertical parts are in a very good superposition in the applicator aperture . For the design of the MTM ZOR applicators, the following dimensions of antenna elements were chosen: in this special discussed case, the length of the vertical part of the antenna is equal to $\lambda/10$. The longitudinal dimension of the unit cell can vary (or be adjusted) in a relatively large range [14]. Depending on the selected size of this dimension, it is necessary to adjust the dimensions of interdigital capacitors. The overall physical dimensions of the applicator prototype are $268 \times 68 \times 70\,\mathrm{mm}$ which represents relative dimensions as follows: the relative width of the aperture is equal to $1/3\lambda_0$, the relative height of the aperture is $1/10\lambda_0$ and the relative depth of the applicator is $1/10\lambda_0$. Alternatively, the MTM ZOR radiating structure can be inserted into the rectangular waveguide section to ensure that the whole radiated power would be perfectly directed to the tissue in the area to be treated. Another possible and interesting use for real clinical therapy is the case where the MTM ZOR radiating structure would be surrounded by metal plates from the top and the back sides and the lateral sides would be made of a dielectric substrate material to ensure that we would not excite the dominant rectangular waveguide mode TE_{10}.

IV. Distribution of SAR created by MTM ZOR in the treated area

To study and verify how these MTM ZOR structures would radiate into the tissue in the area to be treated, several EM simulations of the discussed case (for real conditions of the material) were performed. SAR distribution inside a virtual phantom of the treated region generated by the proposed

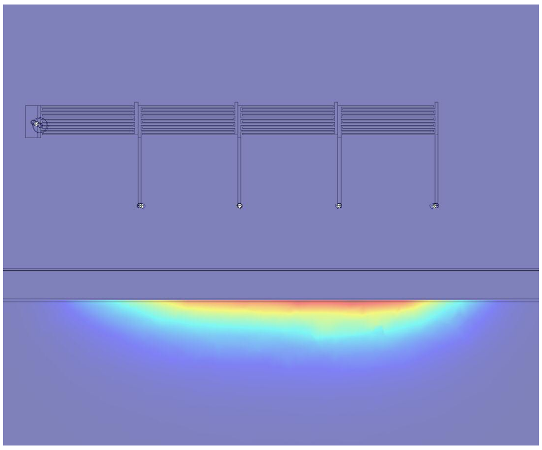


Figure 4. Top view of the applicator, water bolus and the tissue to be treated. SAR distribution in the area to be treated is also displayed here.

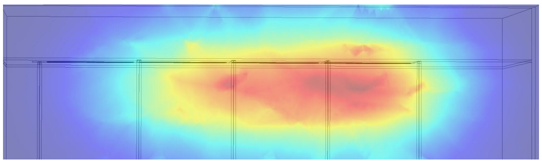


Figure 5. SAR distribution calculated on the surface of the area to be treated.

applicator was investigated using COMSOL Multiphysics® [15]. Muscle tissue parameters were as follows: the real part of the complex permittivity is equal to $\varepsilon_r = 57$ and the equivalent electric conductivity $\sigma_e = 0.81\mathrm{S/m}$ [16]. In the studied model displayed in Figure 4, a water bolus with a thickness of 2 cm was placed between the applicator aperture and the virtual phantom in the area to be treated. The resulting SAR distribution is displayed in two planes in Figures 4 and 5. Figure 4 displays SAR distribution in the plane perpendicular to the applicator aperture, illustrating how EM energy penetrates into the area to be treated. It can be observed that when the EM penetrates the biological tissue, it has very good SAR homogeneity and that the penetration depth is approaching the above mentioned theoretical limit [17].

Figure 5 displays SAR distribution in the plane parallel to the applicator aperture. Homogeneous absorption of EM at the surface of the area to be treated can be observed. Similar distribution of SAR will be observed in all planes parallel to the applicator aperture, but the level of SAR will decrease with increasing depth.

V. Improvement of SAR homogeneity by aid of symmetric feeding of MTM ZOR

The MTM ZOR applicator discussed in this paper and the distribution of SAR achieved by the use thereof (displayed in Figures 4 and 5) can be considered very suitable for practical treatment of cancer patients. As already mentioned in this paper, it approaches the homogeneity level and the effective treatment depth of the plane wave. However, a certain level of asymmetry of SAR distribution is evident in Figures 4 and 5.

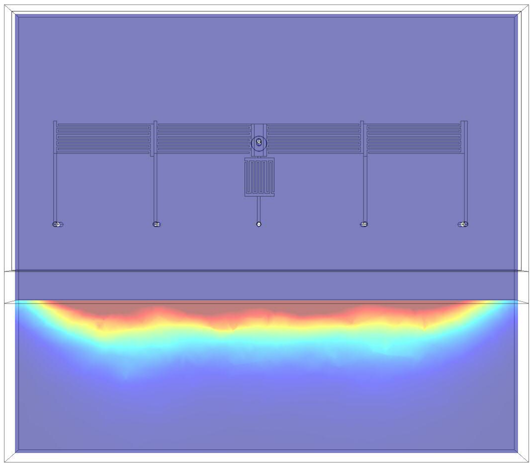


Figure 6. Top view of the applicator with symmetrical feeding, water bolus and the tissue. SAR distribution in the area to be treated is also displayed here.

This effect can be explained by asymmetrical feeding of the MTM ZOR applicator displayed in Figures 5 and 6 and also by the fact that the feeding vertical part has the same phase as the others.

The contribution to radiation is not as it could be if the feeding part would were in the same line as the others. In this part, we would like to propose a modified mechanical and EM arrangement of the MTM ZOR, which would help us improve the homogeneity of SAR distribution in the treated area. As can be seen in Figure 6, a modified MTM ZOR applicator with symmetric feeding is proposed. Furthermore, another vertical radiating part connected to the feeding point via an interdigital capacitor and a section of microstrip TL that was added to ensure the same phase shift as that of the others vertical parts.

The working principle of this MTM ZOR structure is the same as in the previous case. Thanks to the excitation of the zeroth order mode, the vectors of surface current density on all vertical parts of the antenna including the feeding are in phase. Again, we can say that the phenomenon of the Huygens principle can be applied to describe the resulting EM field distribution in the area to be treated. Therefore, the radiated contributions from all vertical parts are in a very good superposition in the applicator aperture. The dimensions of the vertical part of the antenna were chosen to be $\lambda/10$ again. The longitudinal dimension of the unit cell can be vary (be adjusted) in a relatively large range [14]. Based on the choice of this dimension, it is necessary to adjust the dimensions of interdigital capacitors.

In Figs. 6 and 7, it is evident that the homogeneity of SAR in front of five symmetrically feeded radiating parts is much better than the one described in the previous case (chapters 3 and 4). Figure 6 displays SAR distribution in the plane perpendicular to the applicator aperture, illustrating how EM energy penetrates the area to be treated.

Figure 7 displays SAR distribution in the plane parallel to the applicator aperture, illustrating the homogeneity of EM

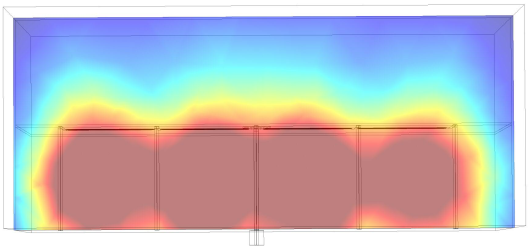


Figure 7. SAR distribution in the plane parallel to the symmetrical fed applicator aperture.

energy absorption at the surface of the area to be treated. Similar distribution of SAR will be observed in all planes parallel to the applicator aperture, but the level of SAR decreases with increasing depth.

VI. Future plans for research of MTM ZOR applicators

Our future research of MTM ZOR applicators will focus on designing several practical clinical applicators and on preparing and performing basic experimental evaluations of these structures in order to verify the promising results presented here, which were obtained by numerical simulations. We consider exploring two basic structure types:

- MTM ZOR structure inserted in the waveguide (thus gaining the advantages of waveguide applicators),
- MTM ZOR structure used as a flat planar applicator.

VII. Conclusions

In this paper, a novel principle for the design of applicators based on MTM structures has been proposed. It has been demonstrated here that when penetrating biological tissue, EM waves generated by the proposed applicators generate very good SAR homogeneity In the near future, we intend to manufacture the proposed structure and to perform an experimental investigation of its properties and of the very promising data obtained in the course of our research using full-wave numerical simulations.

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