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Numerical investigation of novel microwave applicators based on zero-order mode resonance for hyperthermia treatment of cancer

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Abstract

This paper characterizes three novel microwave applicators based on zero-order mode resonators for use in hyperthermia treatment of cancer. The radiation patterns are studied with numerical simulations in muscle tissue-equivalent model at 434 MHz. The relative performance of the applicators is compared in terms of reflection coefficient, current distribution, power deposition (SAR) pattern, effective field size in 2D and 3D tissue volumes, and penetration depth. One particular configuration generated the most uniform SAR pattern, with 25% SAR covering 84% of the treatment volume extending to 1 cm depth under the aperture, while remaining above 58% coverage as deep as 3 cm under the aperture. Recommendations are made to further optimize this structure.

1. Introduction

Metamaterial (MTM) Zeroth-Order mode resonators (ZOR) have been recently introduced and shown potential to improve thermotherapy of cancer [1]. These can be integrated in antenna applicators by improving the homogeneity of electromagnetic (EM) power deposition and the depth of EM wave penetration in tissue under the antenna aperture. With proper assembly, ZOR resonators can

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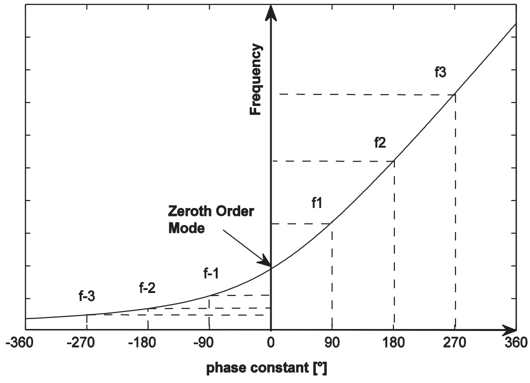

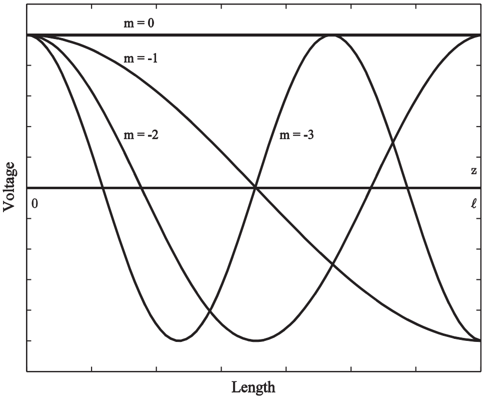

Fig. 1. Relation of the transmission line (TL) and resonant frequencies f of the corresponding resonator (a). Voltage distribution in the case of open-circuited TL of length ℓ (b). Mode $m = 0$ represents the ZOR with infinite guided wavelength.

improve the homogeneity of heating of large areas or conversely localize EM power within well-defined small regions [2]. In addition, ZOR resonators allow the creation of electrically small applicators that work without filling its structure with high dielectric water typical of current clinical applicators. The resultant thinner structure could facilitate the delivery of microwave hyperthermia treatments simultaneous with 3D monitoring of tissue temperature distribution using Magnetic Resonance (MR) thermal imaging which is subject to artefacts from circulating water.

A major advantage of the ZOR phenomenon is that it enables the development of a special kind of resonator whose physical length is completely independent of the classical resonance condition (wavelength), as described in [3]. The phase constant $\beta = 0$ (x axis of Fig. 1a) in this case implies infinite guided wavelength $\lambda_g = 2\pi/|\beta|$ along the MTM structure as well as zero phase shift ($\theta m = -\beta l = 0$) [3]. On the dispersion diagram of Fig. 1a, one can observe the positive (classical $\lambda/2$, λ and $3\lambda/2$) resonances f_1, f_2 and f_3 and negative resonances f_{-1}, f_{-2}, f_{-3}, which correspond to the modes $m = -1$, $m = -2$ and $m = -3$ in Fig. 1b, respectively. Since the Zeroth Order Mode is not dependent on the classical resonant condition of $\lambda/2$ multiplies, this allows us to design the applicator with dimensions matching the clinical need. Moreover, as a result of the spatial arrangement of MTM resonators, the radiation pattern approximates an almost perfect electromagnetic plane wave as it emerges from the aperture and radiates into tissue. This improvement in wave propagation produces the advantage of optimizing homogeneity of power deposition under the aperture with corresponding improvement in uniformity of the temperature distribution throughout the target volume.

In this paper, relevant properties of three novel microwave applicators based on ZOR phenomenon are investigated for use in hyperthermia cancer treatment. Each applicator is modeled using an established commercial numerical simulator, COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden). Relative performance of the three applicators is compared with respect to the homogeneity of power deposition virtually induced in numerical muscle tissue-equivalent model.

2. Applicator design

Three novel MTM applicators were designed for hyperthermia treatments at 434 MHz based on similar ZOR working principles. By exciting the zero-order mode, current density vectors are