GENERATION OF A FOCUSED ELECTROMAGNETIC FIELD INSIDE A TISSUE MEDIUM BY USING SHORT BASEBAND PULSES

K. S. Nikita, G. Mitsis and N. K. Uzunoglu
Department of Electrical and Computer Engineering
National Technical University of Athens
9, Iroon Polytechniou Str, Zografos 15773, Athens, Greece

Abstract-- **The possibility to achieve focusing in a three-layer cylindrical biological tissue model, by using concentrically placed TEM waveguide applicators excited by short baseband pulses, is examined rigorously. The medium response to time harmonic excitation of the TEM array is predicted, by solving the associated boundary value problem. Then, the medium response to pulsed excitation of the array is considered and a Fourier series representation is used in order to obtain the time dependence of the electromagnetic fields produced at any point within tissue. Numerical results are computed and presented and the use of time coincidence is examined, in order to achieve focusing at a specific point of interest within tissue.**

Index term— **focusing, TEM array, baseband pulses, biological tissues**

I. INTRODUCTION

Phased array principles and optimization techniques have been applied in order to achieve focusing of electromagnetic waves inside biological tissue media, mainly within the aim of developing multi-element hyperthermia systems for the treatment of malignant tumors [1]-[3]. However, these techniques suffer from the excessive attenuation of each wave radiated from each individual source and from the side effects created by the coupling phenomena between array source elements [4].

The possibility of using pulsed signals to improve focusing proprrties has been suggested by various researchers using as an additional system parameter the time delay between array signals. Although limited information is presently available on the behaviour of propagation of pulsed signals with baseband spectral content, the behaviour arising from pecoursor phenomena is expected to be useful in focusing elelctromagnetic waves [5].

In most theoretical investigations free space propagation conditions are assumed , while recently focusing properties of waves emitted from TE_{10} rectangular waveguides have been investigated [6]. In the latter case pulsed modulated microwave signals have been considered. In order to investigate the focusing properties of pulsed video signals, sources fed from TEM waveguides could be used. In this direction the selection of a concentric TEM waveguide array is a natural selection meeting the above requirements.

In this paper, the transmission of pulsed baseband signals radiated from a concentric waveguide array in a three-layer cylindrical lossy model is analyzed theoretically. The proposed method is based on the treatment of individual pulses as members of a pulse train with a period T_0, so that the problem is amenable to a Fourier-series analysis. This type of signals has a Fourier series representation for which each member of the discrete spectrum defines the complex amplitude of a time harmonic incident wave. The propagation of the incident field to an observation point within the tissue medium is modelled by using an integral equation technique, in order to solve the associated boundary value problem for each spectral component, and then a Fourier series representation is produced for the transmitted wave field.

II. MATHEMATICAL FORMULATION AND ANALYSIS

The system examined in this paper consists of an arbitrary number (L) of identical parallel-plate waveguide applicators, concentrically placed at the periphery of a three-layer cylindrical lossy model of circular cross section. The three layers can be used to simulate different biological media with dispersive characteristics, such as skin, bone and brain tissues. Alternatively, the two internal layers may be used to simulate biological media (e.g. brain and bone tissues) with the external layer simulating a lossless dielectric medium, which is commonly used to prevent excessive heating of the tissue surface. The dielectric properties of the layers are denoted with the corresponding frequency-dependent relative complex permittivities $\varepsilon_1(\omega), \varepsilon_2(\omega), \varepsilon_3(\omega)$. The free-space

0-7803-5164-9/98/$10.00

wavenumber is $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$, where ε_0 and μ_0 are the free-space permittivity and permeability, respectively. The applicators are filled with a dielectric material of relative permittivity ε_w and relative permeability μ_w and have an aperture size of b circulating around the cylindrical body's surface while their infinite dimension is parallel to the cylindrical body's axis. It is assumed that the apertures are not completely planar and are conforming to the cylindrical body's surface. Radiating apertures are separated by perfectly conducting flanges.

In this study, a Gaussian pulse is considered to be driven to the applicators which is repeated with a period T_0. One period of the time variation of the incident signal of the ℓ th applicator is written as

$$g_\ell(t) = \exp(-\frac{\pi(t-t_\ell)^2}{\tau^2}), \qquad \ell = 1,2,\ldots,L \tag{1}$$

that is centered around the time $t_\ell > 0$, with τ a constant related to the pulse width in time. The associated pulse train $g_{P,\ell}(t)$ has a Fourier series representation,

$$g_{P,\ell}(t) = \sum_{n=-\infty}^{+\infty} c_\ell(n)\exp(jn\omega_0 t) \tag{2}$$

with $\omega_0 = 2\pi / T_0$ the pulse train fundamental angular frequency. Each member of the discrete spectrum $c_\ell(n)$ defines the complex amplitude of a time harmonic wave incident to the applicator and is given by

$$c_\ell(n) = \frac{\tau}{T_0}\exp(-\frac{n^2\omega_0^2\tau^2}{4\pi})\exp(-jn\omega_0 t_\ell) \tag{3}$$

The incident wave distribution on the waveguide apertures is obtained as a spectrum of TEM components,

$$\underline{E}^w_{\ell,t(incid)}(y_\ell, z_\ell = 0; n) = p_\ell c_\ell(n)\underline{e}_t^{EM}(y_\ell) \tag{4}$$

where p_ℓ is the amplitude of the incident TEM mode driven to the ℓ th applicator and $\underline{e}_t^{EM}(y_\ell)$ is the TEM field distribution on the aperture.

The quantity of primary interest in this analysis is the complex transfer function $\underline{F}_\ell(\underline{r};\omega)$, $\ell = 1,2,\ldots,L$ and specifically the discrete spectrum components $\underline{F}_\ell(\underline{r};n\omega_0)$ $= \underline{F}_\ell(\underline{r};n)$, representing the field produced at point $\underline{r}$ inside tissue, when only the ℓ th applicator is excited and the field on its aperture is a continuous time harmonic field ($\exp(+jn\omega_0 t)$) of unit amplitude.

If this response can be predicted, then the instantaneous field at a point of interest inside tissue, due to the pulsed excitation of the array elements, is obtained by summing the contributions made by each transmitted frequency component,

$$\underline{E}(\underline{r};t) = \mathrm{Re}\left\{\sum_{n=1}^{N}\left(\sum_{\ell=1}^{L} p_\ell c_\ell(n)\underline{F}_\ell(\underline{r};n)\right)\exp(jn\omega_0 t)\right\} \tag{5}$$

where Re(.) denotes the real part of the complex exponential form of the time-domain representation of each transmitted frequency component and N is the mode number of the highest frequency component retained for the Fourier series.

Thus, the strategy of the adopted approach is first to predict the medium response, by considering a single time harmonic component at a fixed angular frequency $\omega = n\omega_0$. The time dependence of the field quantities is assumed to be $\exp(+j\omega t)$ and an integral equation technique is adopted, in order to solve the associated boundary value problem.

The fields inside the tissue layers (i=1,2,3) are expressed in terms of cylindrical vector wave functions [7],

$$\underline{E}_i(\underline{r}) = \sum_{m=-\infty}^{m=+\infty}\begin{pmatrix} a_{im}\underline{M}^{(1)}_{m,k}(\underline{r},k_i) + b_{im}\underline{N}^{(1)}_{m,k}(\underline{r},k_i) \\ + a'_{im}\underline{M}^{(1)}_{m,k}(\underline{r},k_i) + b'_{im}\underline{N}^{(1)}_{m,k}(\underline{r},k_i) \end{pmatrix} \tag{6}$$

where $k_i = k_0\sqrt{\varepsilon_i(\omega)}$ and $a_{im}, b_{im}, a'_{im}, b'_{im}$ are to be determined.

Next, the fields inside the waveguide applicators are described as the superposition of the incident TEM mode and an infinite number of all the reflected TEM and TM modes [7], since TE modes are not excited due to the geometry of the structure. Thus, the transverse electric field in the ℓ th applicator ($\ell = 1,2,\ldots,L$), according to the notation of [7], can be written, with respect to the local Cartesian coordinates y_ℓ, z_ℓ of the ℓ th waveguide, as follows:

$$\begin{aligned}\underline{E}^w_{\ell,t}(y_\ell,z_\ell) = {} & A_\ell\underline{e}_t^{EM}(y_\ell)e^{-jkz_\ell} + A'_\ell\underline{e}_t^{EM}(y_\ell)e^{jkz_\ell} \\ & + \sum_{m=1}^{\infty}[\frac{j\lambda_m}{v_m}B'_{\ell,m}\underline{e}^M_{m,t}(y_\ell)e^{j\lambda_m z_\ell}]\end{aligned} \tag{7}$$

where the subscript t is used to denote the transverse field components, A_ℓ is the complex amplitude of the excited TEM mode in the ℓ th waveguide and $A'_\ell, B'_{\ell,m}$ are the complex amplitudes of the reflected TEM, mth order TM modes, respectively, in the ℓth waveguide and k, λ_m are the corresponding propagation constants [7].

By satisfying the continuity of the tangential electric and magnetic field components on the interfaces between different tissue layers and on the contact surface between cylindrical lossy model and radiating apertures, the following system of L coupled integral equations is obtained, in terms of an unknown transverse electric field $\underline{E}_a$ on the waveguide apertures,

$$\sum_{q=1}^{L} \int_{\Gamma_q} \overline{\underline{K}}_{\ell q}(y/y')\underline{E}_{\alpha}(y')dy' = 2A_\ell \left(\frac{k}{\omega\mu_0\mu_w}\right)\underline{h}_t^{EM}(y),$$
$$\ell = 1,2,\ldots,L \qquad (8)$$

where $\underline{h}_t^{EM}$ is the incident TEM mode transverse magnetic field on the aperture of the ℓth waveguide and the kernel matrices $\overline{\underline{K}}_{\ell q}(y/y'), \ell = 1,\ldots,L / q = 1,..,L$ indicate the effect of coupling from the qth aperture $(y') \in \Gamma_q$ to the ℓth aperture $(y) \in \Gamma_\ell$. In order to determine the electric field on the waveguide apertures, the system of integral equations (8) is solved. To this end, a Galerkin's technique is adopted by expanding the unknown transverse electric field on each aperture $\underline{E}_{q,a}$ into wavequide normal modes, as follows

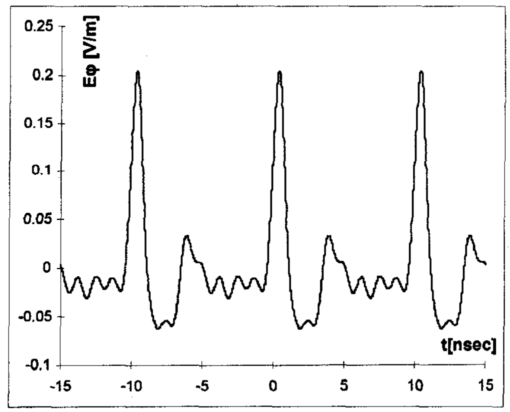
$$\underline{E}_{q,a} = \sum_{m=1}^{\infty}(g_q \underline{e}_t^{EM} + f_{q,m}\underline{e}_{m,t}^{M}), \qquad q = 1,2,\ldots,L \qquad (9)$$

Once the g_q and $f_{q,m}$ expansion coefficients are determined approximately, the aperture fields can be determined approximately and then the electric field at any point inside tissue can easily be computed. Then the dynamic field evolution can be obtained by computing the series of eq.(5)

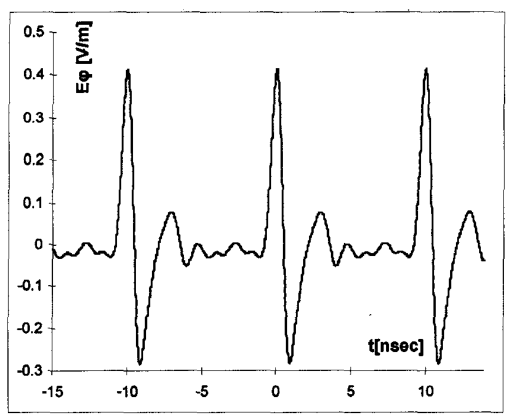
III. Numerical Results and Discussion

The method developed here has been applied to investigate the focusing ability of a concentric array consisting of eight (8) TEM waveguides, at a point of interest inside a two-layer cylindrical biological tissue model, 16 cm in diameter, surrounded by a lossless dielectric layer. The two layers of the biological tissue model are used to simulate bone and brain tissues. The applicators aperture size is defined by $b = 7.5cm$. The aperture centers are placed symmetrically at the periphery of the external dielectric layer. The input signal driven to each applicator is considered to be a Gaussian pulse train, with an individual pulse duration of $\tau = 1ns$, and with a pulse repetition interval of $T_0 = 10ns$.

In an attempt to focus the electromagnetic radiation at a point of interest, within the brain tissue, located at 2 cm depth from the tissue surface on the axis of an applicator, time coincidence of the fields originated from the eight (8)



(a)



(b)

Fig.1: Temporal evolution of the main field component Eφ at a point of interest, located on the axis of an applicator, at 4 cm depth from its aperture. (a) Uniform array excitation. (b) Array excitation adjusted to provide focusing at this point.

waveguides of the array is used. To this end, the discrete spectrum components of the transfer function of each individual applicator are computed and the temporal evolution of the main vector component E_φ of the field originated from each individual applicator at the point of interest is obtained. The latter is used to determine the appropriate time delays to be introduced to the individual pulses, in order to achieve time coincidence of the fields originated from the individual applicators.

The time dependence of the field produced at the point of interest is shown in Fig.1a, for uniform array excitation and in Fig.1b for time excitation, adjusted to achieve time coincidence of the signals at the point of interest.

By comparing Fig.1a with Fig.1b, a 100% increase of the main peak amplitude of the pulse and a 340% increase of the deposited power at the point of interest is achieved by adjusting the excitation of the pulsed signals driven to the individual applicators.

IV. CONCLUSION

A rigorous analysis has been presented for predicting the electromagnetic field produced in a layered cylindrical lossy model by an array of concentrically placed TEM waveguide applicators, excited by pulsed signals with baseband spectral content. Temporal coincidence of the signals has been used, in order to achieve focusing at a point of interest inside a bone-brain biological tissue model.

REFERENCES

[1] J. Chen and O. P. Ghandhi, "Numerical simulation of annular phased arrays of dipoles for hyperthermia of deep seated tumors", *IEEE Trans. Biomed. Eng.*, vol. BME-39, pp. 209-216, 1992.

[2] A. Boag, Y. Leviatan and A. Boag, "Analysis and optimization of waveguide multiapplicator hyperthermia systems", *IEEE Trans. Biomed. Eng.*, vol. 40, pp. 946-952, 1993.

[3] K. S. Nikita, N. G. Maratos and N. K. Uzunoglu, "Optimal steady-state temperature distribution for a phased array hyperthermia system", *IEEE Trans. Biomed. Eng.*, vol. 40, pp. 1299-1306, 1993.

[4] K. S. Nikita and N. K. Uzunoglu, "Coupling phenomena in concentric multi-applicator phased array hyperthermia systems", *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1788-1798, 1996.

[5] P. Wyns, D. P. Fotty and K. E. Oughstun, "Numerical analysis of the precursor fields in linear dispersive pulse propagation", J. Opt. Soc. Am. A, vol. 6, pp. 1421-1429, 1989.

[6] K.S. Nikita and N.K. Uzunoglu, "Analysis of focusing of pulse modulated microwave signals inside a tissue medium", *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1788-1798, 1996.

[7] D. S. Jones, *Theory of Electromagnetism*, Oxford: Pergamon Press, 1964.