GENERATION OF A HIGHLY FOCUSED ELECTROMAGNETIC FIELD IN A LOSSY BIOLOGICAL MEDIUM BY CONTROLING THE PHASE AND TIME EXCITATION OF THE MICROWAVE SOURCES

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ABSTRACT

A focused electromagnetic field is generated in a layered cylindrical biological tissue model, by using a large number of concentrically placed waveguide applicators and pulsed signals of short pulse width, with a high frequency carrier. To this end, constructive phase interference and time coincidence of pulse modulated microwave signals principles are applied. Numerical results are computed and presented for a three-layer geometry, 20 cm in diameter, irradiated by an annular waveguide array, using 30 elements.

INTRODUCTION

Focusing of electromagnetic energy inside biological tissues is a topic of considerable interest in many biomedical applications, such as the treatment of malignant tumors, and inverse scattering problems. Until now, the low microwave spectrum (100-1000 MHz) has been employed and continuous wave concepts have been applied to design and develop hyperthermia systems [1], [2] for cancer treatment, with limited success, mainly due to the excessive loss suffered by each wave radiated from each individual source. Furthermore, the focusing ability of external sources at different points within a biological tissue model may be used to provide appropriate incident fields, in order to reconstruct lossy dielectric bodies, by solving the associated inverse scattering problem [3].

In the present work, an alternative short technique to achieve focusing of pulsed signals (~1 ns pulse width) with a high frequency (9.5 GHz) carrier, using a multi-element concentric waveguide array, is examined. The possibility of employing large number of applicators compared to low frequency systems and the significantly different behavior of pulsed signals has motivated the initiation of this study. The complex transfer function over the frequency-space domain of interest is computed, by using an integral equation technique in order to solve the associated boundary value problem and then, the dynamic field evolution over the entire space-time domain is obtained by numerical inversion of the associated Fourier integral representation.

MATHEMATICAL ANALYSIS

The geometry of a concentric waveguide array looking into a three-layer cylindrical lossy model of circular cross section is shown in Fig.1. The external layer is used to simulate a lossless dielectric medium, which is commonly used to prevent excessive heating of the tissue surface, while the internal two layers are used to simulate different biological media (e.g. bone and brain tissues). The applicators have an aperture size of $a \times b$ ($b<a$) and are placed at the periphery of the lossy model with the large dimension at the transverse direction circulating around the cylindrical surface and the small dimension parallel to the axis of the cylindrical model. An input Gaussian pulse modulated harmonic signal

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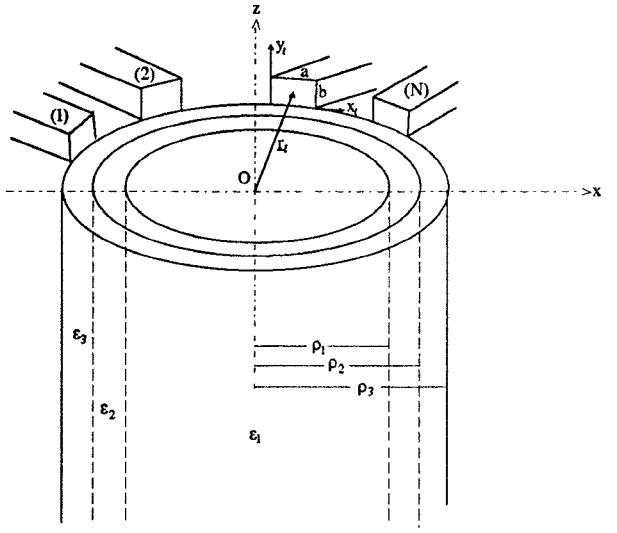

Fig.1: Biological tissue irradiated by a concentric waveguide array.

of fixed carrier frequency ω_0 is considered to be driven to the applicators,

$$g_\ell(t) = \exp(-(t-t_\ell)^2 / 2\tau^2)\cos(\omega_0 t + \psi_\ell),$$
$$\ell = 1,2,\ldots,N \qquad (1)$$

where ψ_ℓ is a phase term of the carrier, $t_\ell > 0$ is the time delay of the injected pulse and τ is a constant related to the pulse width in time. The spectrum of frequencies contained in the pulse modulated microwave signal is obtained from its Fourier transform [4],

$$G_\ell(\omega) = \frac{1}{4\pi} e^{j\psi_\ell} e^{-j(\omega-\omega_0)t_\ell} U(\omega-\omega_0) + \frac{1}{4\pi} e^{-j\psi_\ell} e^{-j(\omega+\omega_0)t_\ell} U(\omega+\omega_0) \qquad (2)$$

where

$U(\omega) = \sqrt{2\pi}\,\tau \exp(-\tau^2\omega^2/2)\exp(j\omega t_\ell)$, is the Fourier transform of the Gaussian envelope.

In order to achieve in practice a stable operation and a good match to the power generator, it is desirable to have only a single propagating mode inside the waveguides. Thus, the instantaneous distribution of the excited field on the aperture of the ℓth applicator is

$$\underline{e}_\ell(x_\ell, y_\ell, z_\ell = 0; t) = p_\ell\, g_\ell(t)\, \underline{e}^{TE}_{1,t}(x_\ell, y_\ell) \qquad (3)$$

where

p_ℓ is the real amplitude of the incident TE_{10} mode driven to the ℓth applicator and

$\underline{e}^{TE}_{1,t}(x_\ell, y_\ell)$ is the TE_{10} field distribution on the aperture.

The quantity of primary interest in this analysis is the complex transfer function $\underline{F}_\ell(\underline{r};\omega)$, ℓ=1,2,...,N representing the field produced at point $\underline{r}$ inside tissue, when only the ℓth applicator is excited and the field on its aperture is a continuous time harmonic field, of unit amplitude and zero phase. If this response can be predicted, then the instantaneous field at a point of interest inside tissue, due to the pulse modulated excitation of the array elements, is obtained in the form of a Fourier inversion integral [4],

$$\underline{E}(\underline{r};t) = \frac{1}{2\pi}\mathrm{Re}\{\exp(j\omega_0 t)\sum_{\ell=1}^{N} p_\ell \exp(j\psi_\ell)\times \int_{-\Delta\omega/2}^{\Delta\omega/2} d\omega\, \underline{F}_\ell(\underline{r};\omega_0+\omega)\, U(\omega)\exp(j\omega(t-t_\ell))\} \qquad (4)$$

where $\Delta\omega$ is the frequency bandwidth of the incident Gaussian pulses.

Thus, the strategy of the adopted approach is first to predict the medium response to a continuous wave excitation of the array. To this end, an $\exp(+j\omega t)$ time dependence of the field quantities is assumed and the associated boundary value problem is formulated and solved, by adopting an integral equation technique [5]. The fields inside the tissue layers are described in terms of cylindrical wave functions satisfying the corresponding wave equations, while the fields inside the waveguides are expanded in terms of guided and evanescent normal modes. By imposing the boundary conditions for the tangential electric and magnetic field components on the $\rho=\rho_1$ and $\rho=\rho_2$ interfaces and on the $\rho=\rho_3$ contact surface

between cylindrical lossy model and radiating apertures, the following system of N coupled integral equations is obtained in terms of an unknown transverse electric field $\underline{E}_a$ on the waveguide apertures

$$\sum_{q=1}^{N} \iint_{\Gamma_q} dx'dy' \overline{\underline{K}}_{\ell q}(x,y/x',y') \underline{E}_a(x',y') =$$

$$2p_\ell e^{j\psi_\ell} \underline{h}_{1,t}^{TE}\left(\frac{j\gamma_1}{u_1}\right) \quad \ell,q = 1,2,\ldots,N \qquad (5)$$

where the notation of [6] has been adopted, $\underline{h}_{1,t}^{TE}$ is the incident TE_{10} mode transverse magnetic field on the aperture of the ℓth waveguide, and the kernel matrices $\overline{\underline{K}}_{\ell q}(x,y/x',y')$ indicate the effect of coupling from the qth aperture $(x',y') \in \Gamma_q$ to the ℓth aperture $(x,y) \in \Gamma_\ell$. In order to solve this system, a Galerkin's procedure is adopted by expressing the unknown electric fields on the apertures in terms of the corresponding waveguide mode fields. Once the aperture fields are determined, the electric field distribution within tissue can be easily computed and then the dynamic field evolution can be obtained by computing the Fourier inversion integral (4).

NUMERICAL RESULTS AND DISCUSSION

The method developed here, has been applied to provide focusing at different points in a cylindrical tissue model, 16 cm in diameter, irradiated by a concentric array, using 30 waveguide applicators. The body model consists of two layers, simulating bone and brain tissues and it is surrounded by a 2 cm thick lossless dielectric layer. The applicators of the array have an orthogonal aperture of 2×1 cm^2 size and are placed symmetrically at the periphery of the external dielectric layer. A time-dependent Gaussian pulse of 1 ns pulse width is used to modulate a microwave carrier of fixed frequency 9.5 GHz.

In order to provide focusing at a target point within biological tissue, the main component of the transfer function of each applicator ($F_{\ell z}$, ℓ=1,2,...,30) at the point of interest is computed and its phase at the carrier frequency is used to determine the appropriate phase excitation for the microwave sources, in order to achieve constructive phase interference at this point. Furthermore, the temporal evolution of the main field component E_z originated from each individual applicator at the point of interest is used to determine the appropriate time delays to

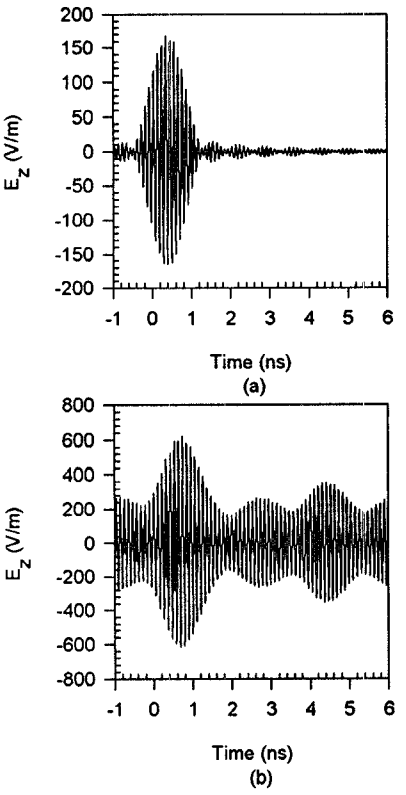

Fig.2: Temporal evolution of the main field component E_z at a point of interest, located on the axis of an applicator, at 4 cm depth from its aperture. (a) Uniform array excitation. (b) Array excitation adjusted to provide focusing at this point.

be introduced to the pulse envelopes, in order to achieve time coincidence of the fields originated from the individual applicators. In Figs.2a,b the temporal evolution of the main field component E_z is shown, at a point of interest, located on the axis of an applicator, at 4 cm depth from the applicator's aperture for uniform array excitation ($p_1=...=p_{30}=1$, $\psi_1=...=\psi_{30}=0$, and $t_1=...=t_{30}=0$), and for time and phase excitation adjusted to provide focusing at this point, respectively.

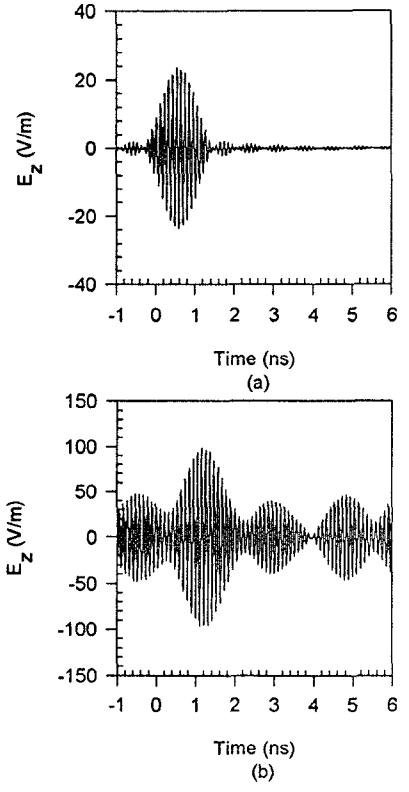

Fig.3: Temporal evolution of the main field component E_z, at a point of interest, located on the axis of an applicator, at 5 cm depth from its aperture. (a) Uniform array excitation. (b) Array excitation adjusted to provide focusing at this point.

In Figs.3a,b, a new point of interest, located at 5 cm depth from the applicator's aperture, is considered, and the temporal evolution of the main field component is presented, for uniform array excitation and for excitation adjusted to provide focusing at the new target point, respectively. It can be observed that, by adjusting the phase and time excitation of the microwave sources, a considerable increase of the main peak amplitude of the pulse is achieved. The proposed method can be used as a means for solving the electromagnetic inverse scattering problem of cylidrical lossy dielectric bodies [3].

CONCLUSION

Temporal coincidence and constructive phase interference of pulse modulated microwave signals radiated by a large number of concentrically placed waveguide applicators are used, in order to achieve focusing in a layered cylindrical lossy model.

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