RELATIVE HEATING PATTERN DUE TO 4×3 PLANAR ARRAY OF WATER-LOADED BOX-HORN FOR HYPERTHERMIA TREATMENT OF CANCER

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ABSTRACT

In this paper, the authors have analyzed theoretically the heating pattern due to 4×3 planar array of water-loaded box-horns. Each box-horn of the array is assumed to be filled with water to provide better impedance matching to bio-medium. Loading box-horn with water also reduce its size that makes it suitable for array application. Expression for electric field is derived and relative heating pattern is evaluated at 2.45 GHz for a planar array of water-loaded box-horns in direct contact with a heating medium (muscle). The present analysis is carried out using Fresnel-Kirchhoff scalar diffraction field theory. It has shown that 4×3 planar array of water-loaded box-horns has wider lateral area of heating pattern in x- and y-directions and higher depth of penetration in z-direction in comparison to single water-loaded box-horn. The present theory can be used to develop a planar array of water-loaded box-horns for hyperthermia treatment of cancer at any location.

INTRODUCTION

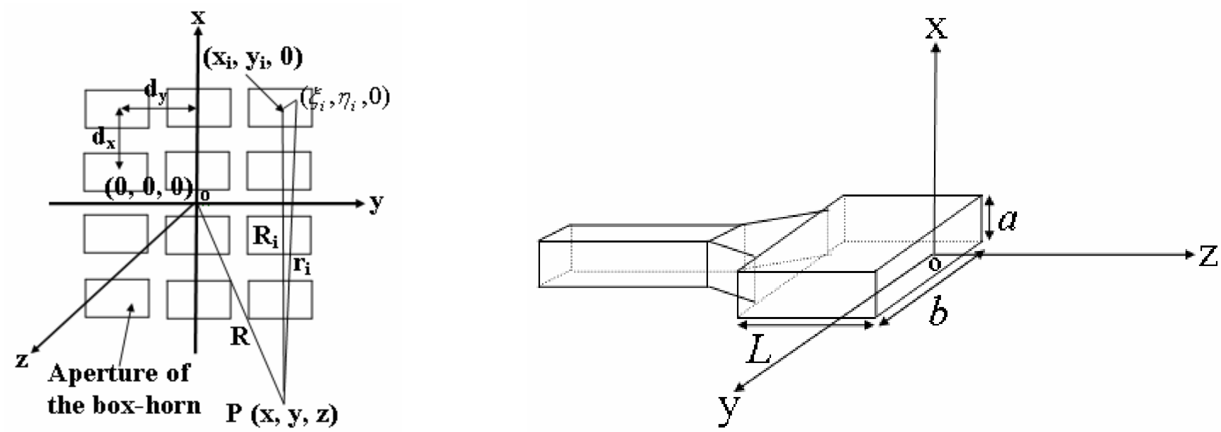
Hyperthermia [1] is a technique for treatment of cancer, wherein the tumor is heated upto the therapeutic temperature (43-50^0 C) so that the cancer cells can be selectively killed without damaging surrounding normal tissue. Hyperthermia has been shown to be effective in the treatment of cancer, especially when combined with chemo- or radio-therapy. In this paper, the authors have proposed a planar array of box-horns for hyperthermia treatment of cancerous tumor. The box-horn [2] consists of a TE_{10} mode H-plane sectoral-horn coupled to a length L of rectangular waveguide of same E-plane height but whose H-plane width is large enough to support the TE_{30} mode. The field over the box-horn aperture is then a combination of the TE_{10} and TE_{30} modes. The amplitude distribution over the H-plane of the box-horn aperture is a closer approximation to the uniform distribution whereas TE_{10} mode provides cosine variation of the field.

Research has shown that heating pattern associated with many applicators [1] are such that the effective heating region (e.g., defined by the -3-dB contour) can be significantly smaller than the area defined by the dimensions of the applicators. A further limitation of a single applicator is that the hot spot cannot be changed during use, making it difficult to improve the non-uniform temperature distributions that are invariably produced during the treatment of patients. The planar array of box-horns can be used to change the location of the hot spot toward any point in the bio-medium.

Expression for electric field is derived for a 4×3 planar array of water-loaded box-horn in direct contact with a heating medium (muscle). The relative heating pattern is evaluated at 2.45 GHz, one of the ISM frequencies for a box-horn planar array. Each box-horn of the array is filled with water to provide better impedance matching to bio-medium. Loading water inside the box-horn reduces reflection between box-horn aperture and bio-medium and also its size, which makes it suitable for array. The present analysis is based on Fresnel-Kirchhoff scalar diffraction field theory [3]. It has been reported that 4×3 planar array of water-loaded box-horns provides wider lateral area of heating pattern in x- and y-directions in comparison to single water-loaded box-horn. Hence the large size tumors can be treated with the array applicator easily. It is also seen that 4×3 planar array of water-loaded box-horns gives higher depth of penetration in comparison to single water-loaded box-horn, so that cancerous tumor at greater depth can be heated with the present array applicator. By increasing number of box-horns in the array, greater depth of penetration can be achieved.

ANALYSIS OF HEATING PATTERN IN MUSCLE LAYER DUE TO 4×3 PLANAR ARRAY OF WATER-LOADED BOX-HORNS

The aperture of 4×3 planar array of water-loaded box-horns terminated in heating-medium (muscle) and three-dimensional view of a box-horn are shown in Figs.1 (a) and (b), respectively. The muscle layer has complex permittivity of ε_m^*. The narrow and broad dimensions of the aperture and length of each box-horn are denoted as *a*, *b* and *L* respectively. The center to center separation between two adjacent box-horns is d_x and d_y in x- and y-directions, respectively.



(a) (b)

Fig. 1. (a) 4×3 planar array of water-loaded box-horns terminated in heating medium and (b) three-dimensional view of a water-loaded box-horn

In present analysis, muscle is considered to be extending upto infinity along positive z-direction, mutual coupling between any two horn applicators is neglected, since reported mutual coupling between adjacent elements is on the order of -30 dB, presumably low due to medium losses [1].

Let the centre of ith box-horn in the planar array be situated at the point $(x_i, y_i, 0)$ and the coordinates of field point P of the array be (x, y, z). It is considered that the coordinates of a point in the aperture of ith box-horn with the centre of that box-horn acting as the origin to be $(\xi_i, \eta_i, 0)$. The electric-field in muscle region due to the ith box-horn of the array can be found by Fresnel-Kirchhoff scalar diffraction theory [3] as written below.

$$E_i(P) = \frac{1}{4\pi}\int_{\xi_i}\int_{\eta_i} E(\xi_i, \eta_i, 0).\frac{e^{-jkr_i}}{r_i}.\left[\left(jk_m + \frac{1}{r_i}\right)\cos(n_i, r_i) + jk_m \cos(n_i, s_i)\right] d\xi_i d\eta_i \tag{1}$$

where i=1, 2…12, $k_m = (2\pi f\sqrt{\mu_0\varepsilon_0\mu_r\varepsilon_m^*})$ is the complex propagation constant of the muscle, f is the operating frequency of the box-horn. (n_i, r_i) is the angle between the normal to the aperture face of ith box-horn and r_i direction. (n_i, s_i) is the angle between the same normal and phase illumination direction across the aperture of ith box-horn. r_i is given by.

$$r_i = \left[\{x - (x_i + \xi_i)\}^2 + \{y - (y_i + \eta_i)\}^2 + z^2\right]^{1/2} \tag{2}$$

The electric field at the aperture of ith box-horn [1] is represented by

$$E(\xi_i, \eta_i, 0) = a_{10}\cos\left(\frac{\pi\eta_i}{b}\right)e^{-j\beta_{10}L} + a_{30}\cos\left(\frac{3\pi\eta_i}{b}\right)e^{-j\beta_{30}L} \tag{3}$$

where a_{10} and a_{30} are amplitude coefficients for TE_{10} and TE_{30} modes respectively, β_{10} and β_{30} are the phase constants for corresponding modes.

For practically all aperture antennas that concentrate microwave energy along the z-axis, angle (n_i , s_i) is very nearly zero, so that $\cos(n_i , s_i)$ may be taken as unity. The angle (n_i , r_i) can be evaluated by the relation $(n_i , r_i) = \cos^{-1}(z/r_i)$. Therefore, the near field at $P(x, y, z)$ due to ith box-horn of the planar array responsible for heating the medium can be put in the simplified form as

$$E_i(P) = \frac{1}{4\pi}\int_{-a/2}^{a/2}\int_{-b/2}^{b/2} E(\xi_i,\eta_i,0).\frac{e^{-jk_m r_i}}{r_i}.\left[jk_m\left(1+\frac{z}{r_i}\right)+\frac{z}{r_i^2}\right]d\xi_i d\eta_i \tag{4}$$

The final integral expression for the field $E_i(P)$ is found by substituting the expressions for r_i and $E(\xi_i , \eta_i,0)$ from (2) and (3) into (4) The total electric field E_t at point $P(x, y, z)$ due to complete planar array of box-horns [1] is given by:

$$E_t(P) = \sum_i E_i(P) \tag{5}$$

The heating power per unit volume [4] in bio-medium can be found by

$$P = \frac{1}{2}\sigma_m |E_t|^2 \tag{6}$$

where E_t is the total electric field amplitude in muscle and $\sigma_m (= \omega\varepsilon_0\varepsilon''_m)$ and ε''_m are the conductivity and imaginary part of relative permittivity of muscle layer respectively.

DESIGN OF 4×3 PLANAR ARRAY OF WATER-LOADED BOX HORNS

Each water-loaded box-horn of the array is designed as per Silver [2]. Theoretical analysis of box-horn [2] shows that ratio a_3 /a_1 equal to 0.3 is a fairly good approximation to uniform illumination. The box-horn is especially useful, therefore for the application requiring tenth-power beam-width around 60° with box-aperture b=1.6λ. The computed dimensions of the each box-horn of the array at 2.45 GHz are a=0.43 cm, b=2.23 cm, L =1.16 cm and the flare angle of the horn exciting the box is 30^0 in H-plane. The permittivity of the water is taken to be 77–j12.09 [5] for designing water-loaded box-horn. The complex permittivity [6] of muscle is taken to be $\varepsilon^*_m = 47.5 - j13.5$ at 2.45 GHz in the calculation of relative heating pattern. The separation between the boundaries of two adjacent box-horns is taken to be 0.5 cm in both x- and y-directions.

RESULTS AND DISCUSSION

The three-dimensional view of heating pattern in muscle layer in x-y plane for 4×3 planar array of water-loaded box-horns is computed at 2.45 GHz using MATLAB and results are presented in Fig. 2. The values of heating power per unit volume are normalized to the maximum value of heating power per unit volume in the muscle layer. Fig. 3 depicts three-dimensional view of heating pattern in muscle layer in x-y plane for single water-loaded box-horn at 2.45 GHz. It can be observed from Figs. 2 and 3 that 4×3 planar array of water-loaded box-horns has a marked advantage over single applicator in that significant levels of heating power are produced over a larger area beneath the array applicator.

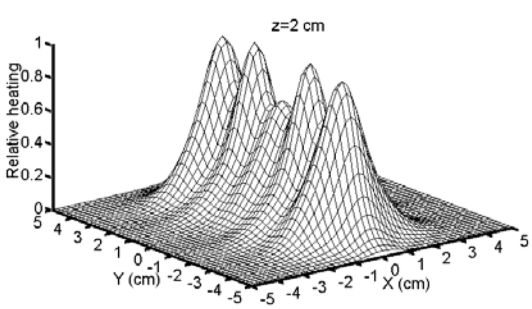


Fig. 2. Relative heating pattern in muscle medium due to 4×3 planar array of water-loaded box-horns along x-y directions

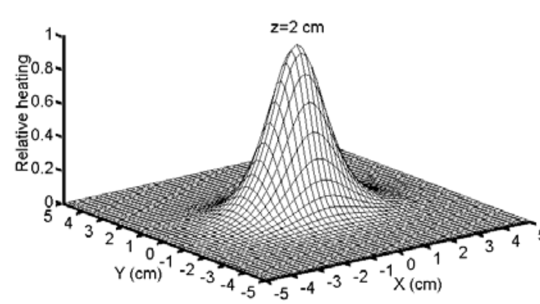


Fig. 3. Relative heating pattern in muscle medium due to single water-loaded box-horn along x-y directions

The relative heating power pattern at 2.45 GHz due to 4×3 planar array of water-loaded box-horns is compared with that for single water-loaded box-horn in z-direction. The value of heating power per unit volume of planar array and single box-horn are normalized with the maximum value that occurs for the 4×3 planar array. Fig. 4 reveals that depth of penetration in heating-medium for 4×3 planar array of water-loaded box-horns is higher in comparison to that for single water-loaded box-horn.

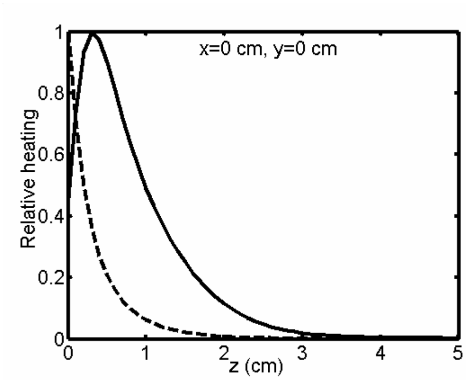


Fig. 4. Relative heating pattern in muscle due to planar array of box-horns and single box-horn along z-direction

CONCLUSION

A theoretical analysis has been presented for heating pattern in muscle layer illuminated by planar array of water-loaded box-horns. It is investigated that planar array of water-loaded box-horns can heat wider tumor area in xy-plane in comparison to single water-loaded box-horn. Also, 4×3 planar array of water-loaded box-horns provides deeper penetration than the single water-loaded box-horn. Greater depth of penetration can be obtained by employing more number of box-horns in the array, but this increases complexities of the array. By changing phase and amplitude excitation each of the box-horns of the array, the desired shape and location of relative heating pattern according to shape and location of tumor can be obtained. The results presented here may be helpful in analyzing, designing and developing desired planar array of water-loaded box-horns for hyperthermia treatment of cancer. Since the dielectric properties of skin are almost identical to those of muscle, the results presented here may be applied to the portions of the body having negligible fat and bone thicknesses in practical terms.

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