Coherent 3×3 Planar Array of Water-Loaded Box-Horns for Hyperthermia Treatment of Cancer

Ramesh Chandra Gupta and S. P. Singh

Abstract—**In this paper, the authors have proposed a 3×3 planar array of water-loaded box-horns for hyperthermia treatment of tumor. The box-horn 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. Thus box-horn supports TE_{10} and TE_{30} modes resulting in relatively uniform amplitude distribution over the H-plane of the aperture to prevent steep heating gradient in bio-medium. Expression for electric field in muscle due to planar array of box-horns is derived using two different techniques, i.e., Fresnel-Kirchhoff scalar diffraction field theory and plane wave spectral technique. SAR distributions in different planes of heating medium due the array applicator are evaluated at 2.45 GHz using these techniques. The results for SAR distribution of the planar array of box-horns are also compared with those for single box-horn. The results for SAR distribution in z-direction demonstrate that tumor at greater depth can be heated with the planar array of box-horns due to increased penetration depth in comparison to a single box-horn. Also planar array has wider area of illumination and higher peak value of SAR in both x- and y-directions as compared with a single box-horn. It is shown that the results obtained by these two techniques are in agreement with each other.**

Index Terms—**Cancer, hyperthermia, planar array of box-horns, specific absorption rate (SAR).**

I. INTRODUCTION

MICROWAVE hyperthermia is a technique to treat cancerous tumors, wherein the temperature throughout the cancerous tumor is elevated to the therapeutic temperature range (43 °C to 50 °C). A single dielectric-loaded waveguide applicator [1], multimodal applicator [2], conical horn antenna [3], etc. are often used for hyperthermia treatment of cancer. Numerous array configurations have been investigated including different types of applicators in the last two decades [4], [5]. Research has shown that field distribution associated with many applicators is such that the effective treatment field size (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 field cannot be modified during use, making it difficult to improve the non-uniform temperature distributions that are invariably produced during the treatment of patients. In this paper, authors have proposed and analyzed a 3×3 coherent planar array of box-horns in direct contact with muscle medium for hyperthermia treatment of tumor at 2.45 GHz. The planar phased array of box-horns can be used to change the position of the hot spot toward any point in bio-medium (muscle). The box-horn [6] consists primarily of a piece of waveguide of length L, frequently referred to as a 'box' , whose magnetic plane dimension is large enough to support TE_{10} and TE_{30} modes. The resultant field distribution over the box-horn aperture along H-plane width thus becomes a closer approximation to the uniform distribution to prevent steep heating gradient in muscle. Each box-horn is assumed to be filled with water. Loading the box-horn with water provides a good impedance match and ensures good transmission into the tissue. Also, it reduces the size of the box-horn, which makes it suitable for array configuration.

The expression for electric field distribution in muscle-medium due to coherent planar array of box-horns is derived using two different methods, i.e., Fresnel-Kirchhoff scalar diffraction field theory [6], [7] and plane wave spectral technique [8], [9] and SAR distribution is computed at 2.45 GHz. Good agreement between the results obtained by these two methods has been observed. The results for SAR distribution of planar array are compared with those for single box-horn.

II. ANALYSIS OF SAR DISTRIBUTION IN MUSCLE DUE TO COHERENT PLANAR ARRAY OF BOX-HORNS

The aperture of 3×3 planar array of box-horns terminated in muscle layer is illustrated in Fig. 1(a). The three-dimensional view of a box-horn is shown in Fig. 1(b).

The narrow and broad dimensions of the aperture of each box-horn are denoted as a and b, respectively. The length of each box along z-direction is denoted as L. The center to center spacing between two adjacent box-horns is d_x in x-direction and d_y in y-direction. A muscle layer has complex permittivity of ε_m^*. In present analysis each box-horn aperture is assumed to be in direct contact with the muscle surface. Muscle is a highly lossy medium ($\varepsilon_m^* = 47.5 - j13.5$ at 2.45 GHz) [10], and its thickness varies from about 3 cm to 6 cm. The SAR value beyond 3 cm in muscle is almost zero at the frequency used.

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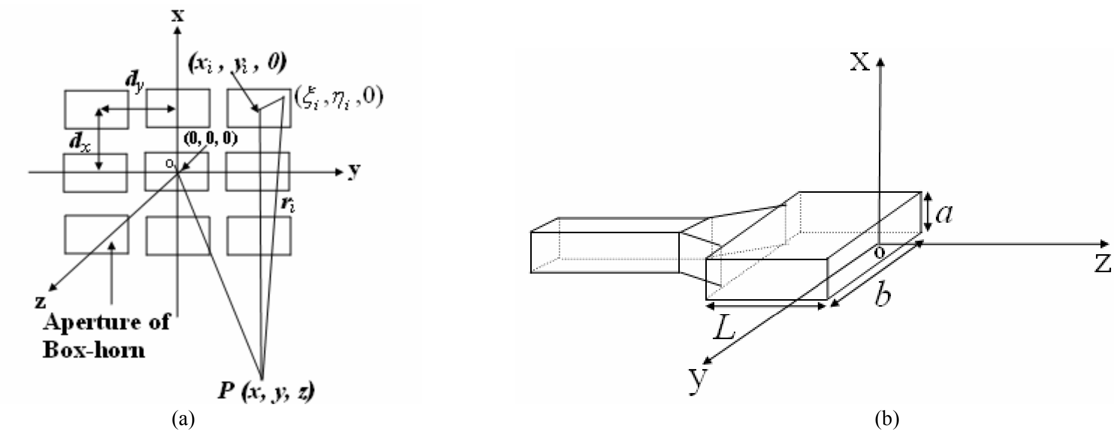


Fig. 1. (a) 3×3 planar array of box-horns terminated in muscle medium and (b) three-dimensional view of a box-horn.

Hence, 3-6 cm thick muscle is equivalent to infinitely thick medium. Therefore, muscle in present case may be considered to extend up to infinity along z -direction.

In an array environment, the element pattern is affected by the mutual coupling between the elements. Loane *et al.* [11] investigated experimentally that coupling between adjacent waveguide elements is on the order of -30 dB, presumably low due to high medium losses. Nikita and Uzunoglu [12] have shown semi-analytically that the magnitude of the mutual coupling in non-infinite three-layered (skin, fat, and muscle) tissue model for phased array of waveguide applicator is influenced by the frequency, aperture size of each applicator, and distance between the elements of the array. At higher frequency (915 MHz), the coupling between neighboring applicators is of the order of -20 dB. The mutual coupling also depends on configuration of the array and impedance matching between applicator and the tissue. In the present configuration, the box-horn applicator is designed at higher frequency (2.45 GHz) and is filled with water. Therefore, its impedance matches well with bio-medium. The spacing between elements of the array is kept more than what is required to accommodate the array elements and the configuration of the array is planar. The aperture size of box-horn is larger than the waveguide carrying TE_{10} mode at same frequency. All these factors reduce mutual coupling. Therefore, for non-infinitely thick skin/fat/muscle layers as well as infinite muscle layer; it is true that mutual coupling between elements of the array will be of the order -20 dB or lower. Hence, mutual coupling effect is usually considered to be secondary and is neglected in this study. This approximation gives satisfactory results for the calculation of SAR distribution.

A. Analysis of SAR in Heating-Medium Due to 3×3 Coherent Array of Box-Horns Using Fresnel-Kirchhoff Scalar Diffraction Field Theory

Let centre of i -th box-horn in the array is situated at the point $(x_i, y_i, 0)$ and the coordinates of field point P be (x, y, z). Assume the coordinates of a point in the aperture of i -th box-horn with the centre of that box-horn acting as the origin to be $(\xi_i, \eta_i, 0)$. The near-field in muscle region due to the i -th box-horn of the array can be found by Fresnel-Kirchhoff scalar diffraction theory [6], [7] as follows

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

where $i = 1,2,..,9$; (n_i, r_i) =angle between the normal to the aperture face of i -th box-horn and r_i direction; (n_i, s_i) =angle between the same normal and phase illumination across the aperture of i -th box-horn; $k_m = \omega\sqrt{\mu_0\varepsilon_0\mu_r\varepsilon_m^*}$ is the complex propagation constant of the muscle; and

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

The electric field, $E(\xi_i, \eta_i)$ at the aperture of i -th box-horn [6] is represented by

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

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.

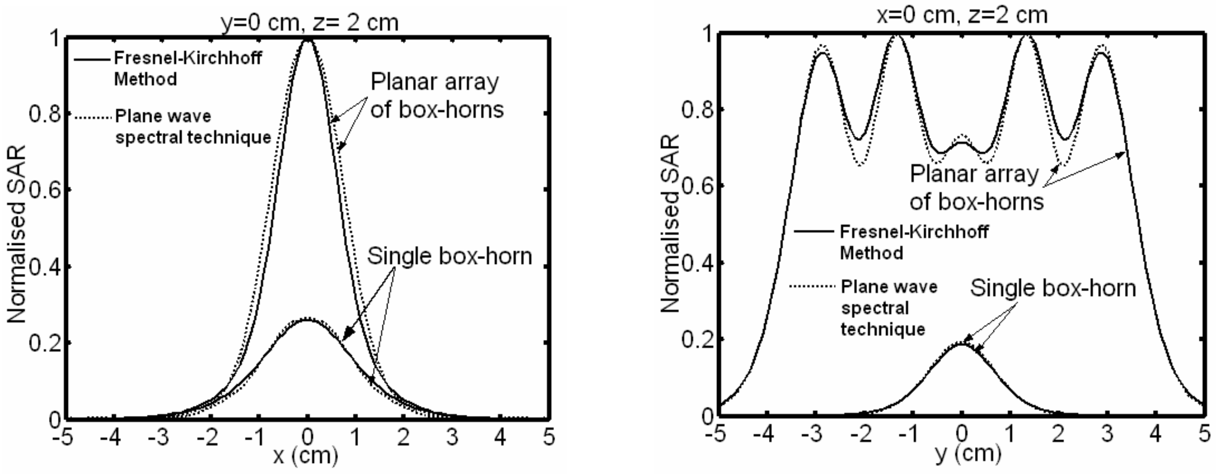
For nearly all aperture illuminations that concentrate energy along the z-axis, angle(n_i, s_i) is very nearly zero, so that $\cos(n_i, s_i)$ may be taken as unity. The angle(n_i, r_i) can be found by the relation $(n_i, r_i) = \cos^{-1}(z/r_i)$. Therefore, the near field at $P(x, y, z)$ due to i -th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

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

The final integral expression for the field $E_i(P)$ is found by substituting the expressions for r_i and $E(\xi_i, \eta_i)$ from (2) and (3) into (4).

B.Analysis of SAR in Heating-Medium Due to 3×3 Coherent Array of Box-Horns Using Plane Wave Spectral Technique

The analysis of fields in the heating-medium presented here follows the plane wave spectral technique discussed by Compton [8] and Harrington [9]. The *x*-component of electric field at the aperture of i -th box-horn of the array [6] is represented by



(a) (b)

Fig. 2. Comparison of SAR distributions in muscle due to planar array of box-horns and single box-horn along, (a) x-direction and (b) y-direction.

$$E_{xi}(x,y,0)=a_{10}\cos(\frac{\pi y}{b})e^{-j\beta_{10}L}+a_{30}\cos(\frac{3\pi y}{b})e^{-j\beta_{30}L} \quad (5)$$

With the aperture electric field as given in (5), the fields in heating-medium are every-where TE to y [8], [9]. Hence, the fields may be represented by an electric vector potential

$$\bar{F}=\hat{y}\psi \quad (6)$$

where ψ is solution of the wave equation

$$\nabla^2\psi+k_m^2\psi=0 \ . \quad (7)$$

The solution for i -th box-horn of the array, ψ_i may be constructed as the sum of a continuous spectrum of eigenvalues as follows

$$\psi_i(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f(k_x,k_y)\, e^{-jk_z(z-z_i)}e^{-jk_x(x-x_i)}e^{-jk_y(y-y_i)}dk_x dk_y \quad (8)$$

where $k_z=\sqrt{k_m^2-k_x^2-k_y^2}$ and $f(k_x,k_y)$ is the plane wave spectra in heating medium (muscle region).

The electric field may be found from the relation

$$\bar{E}=-\nabla\times\bar{F} \quad (9)$$

The x-, y- and z-components of electric field in heating medium due to i -th box-horn of the array are derived with the help of (6), (8) and (9) and expressions for the components of the field are given below

$$E_{xi}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}-jk_z f(k_x,k_y)\, e^{-jk_z(z-z_i)}e^{-jk_x(x-x_i)}e^{-jk_y(y-y_i)}dk_x dk_y \quad (10)$$

$$E_{yi}(x,y,z)=0 \quad (11)$$

$$E_{zi}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}jk_x f(k_x,k_y)\, e^{-jk_z(z-z_i)}e^{-jk_x(x-x_i)}e^{-jk_y(y-y_i)}dk_x dk_y \quad (12)$$

Substituting for the field $E_{xi}(x,y,0)$ from (5) and taking inverse Fourier transform of (10) at $z=0$ gives

$$f(k_x,k_y)=\frac{j.4\pi b}{k_x k_z}\sin(\frac{k_x a}{2})\cos(\frac{k_y b}{2}) \left[\frac{a_{10}e^{-j\beta_{10}L}}{\pi^2-b^2k_y^2}-\frac{3a_{30}e^{-j\beta_{30}L}}{9\pi^2-b^2k_y^2}\right] \quad (13)$$

The x-, y- and z-components of electric field, E_{xi} , E_{yi} and E_{zi} for i -th box-horn of the array can be found by substituting (13) in (10)-(12). The magnitude of total electric field at field point P due to i -th box-horn of the array can be evaluated by

$$E_i(P)=\sqrt{|E_{xi}|^2+|E_{yi}|^2+|E_{zi}|^2} \ . \quad (14)$$

The total electric field E_t at point $P(x,y,z)$ due to entire coherent 3×3 planar array of box-horns [4] is given by

$$E_t(P)=\sum_i E_i(P) \quad (15)$$

The specific absorption rate (*SAR*) in muscle can be evaluated by

$$SAR=\frac{\sigma_m|E_t|^2}{2\rho_m} \quad (16)$$

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

III. Design of Planar Array of Box Horns

The water-loaded box-horn applicator is designed at 2.45 GHz as discussed by Silver [6]. For sake of brevity, design procedure is not given here. The computed dimensions of the box-horn 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 water is taken to be equal to $77-j12.09$ [13]. The separation between two adjacent box-horns can be taken as $d_x=d_y=n\lambda_m/2$, where $n=1,2,3,...$ and λ_m is wavelength in muscle. Due to aperture dimension constraints, separation between two adjacent box-horns is taken to be $d_x=\lambda_m/2$ in x-direction and $d_y=3\lambda_m/2$ in y-direction.

IV. Validation of the Theory

To validate the analysis, the SAR distributions due to coherent 3×3 planar array of box-horns and single box-horn in x-, y- and z-directions are computed using Fresnel-Kirchhoff scalar diffraction field theory and compared with

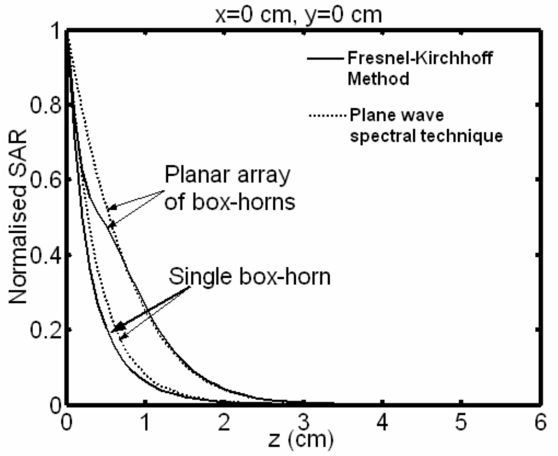


Fig. 3. SAR distributions in muscle due to planar array of box-horns and single box-horn along z-direction.

those obtained by plane wave spectral technique as shown in Figs. 2 and 3. The SAR distributions obtained by both analysis techniques are in good agreement with each other (Figs. 2 and 3).

V. Numerical Results And Discussion

The SAR distributions in muscle layer for 3×3 planar array of water-loaded box-horns are computed at 2.45 GHz using MATLAB® and results are presented in Figs. 2-4. The complex permittivity [10] and density [14] of muscle are taken to be $\varepsilon_m^* = 47.5 - j13.5$ and $\rho_m = 1050$ kg/m^3, respectively in the computation of SAR.

In Figs. 2(a)-(b) the SAR distributions at 2.45 GHz due to 3×3 planar array of box-horns are compared with those for single box-horn in x-and y-directions respectively. The SAR value is normalized with maximum value of SAR that occurs for planar array of box-horns in muscle layer. It is observed from Fig. 2 that planar array has wider area of illumination and higher peak value of SAR in both x -and y -directions as compared with single box-horn. Therefore, coherent planar array of box-horns has a marked advantage over single applicator in that significant levels of absorbed power are produced over a larger area beneath the array applicator.

SAR distributions along z-direction are compared in Fig. 3 for planar array and single box-horn. Fig. 3 reveals that penetration depth for planar array of box-horns is higher than that for single box-horn. Thus, planar array can be used to treat deep-seated tumor.

Fig. 4 illustrates the three-dimensional SAR distribution in x-y, x-z and y-z planes for 3×3 coherent planar array of water-loaded box-horns at 2.45 GHz. The SAR values are normalized to the maximum value of SAR in muscle layer. It can be inferred from Fig. 4 that effective heating sizes (-3 dB contour) in the three given planes are continuous and uniform implying the uniformity of heating.

VI. Conclusions

An analytical solution has been presented for SAR distribution in muscle layer illuminated by planar array of water-loaded box-horns. It is shown that planar array of box-horns can heat wider tumor area and has higher SAR values in comparison to single box-horn. Also, 3×3 planar array of box-horns provides deeper penetration than the

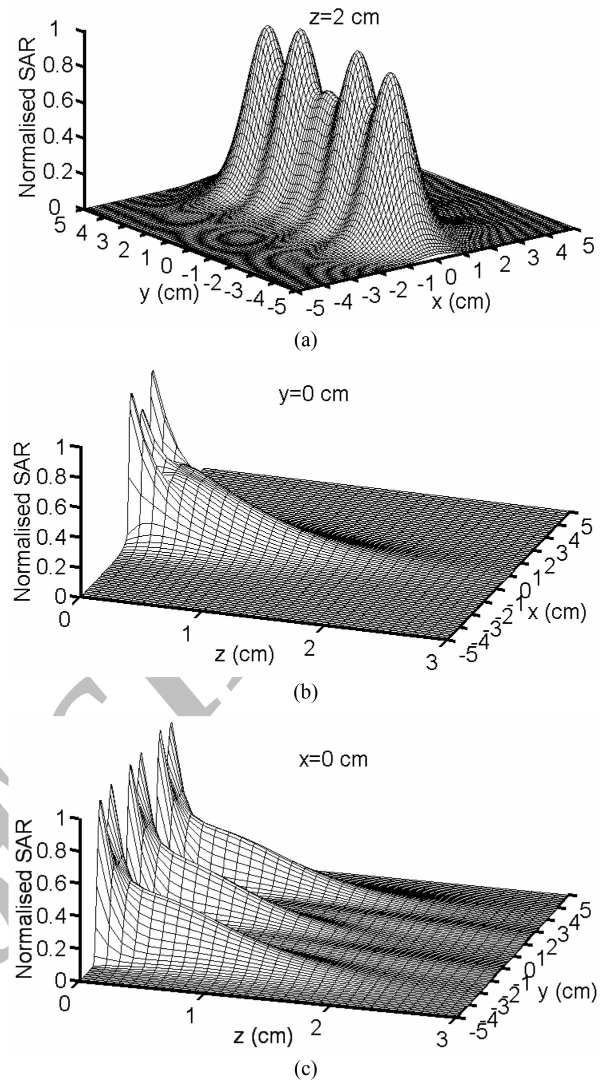


Fig. 4. SAR distribution in muscle medium due to box-horn at 2.45 GHz along, (a) x-y plane, (b) x-z plane, and (c) y-z plane.

single box-horn. The SAR distribution and position of hot spot can be changed by changing phase and amplitude excitations of each box-horn of the array. The matter presented in the paper may be useful in analyzing, designing and developing desired planar array of box-horns for hyperthermia. Since the dielectric properties of skin are almost same as those of muscle, the results presented here may be applied to the portions of the body having negligible fat thickness.

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