Elliptically bent conformal phased array of modified box-horns for hyperthermia treatment of tumors

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[1] A novel and effective hyperthermia applicator utilizing an elliptically bent conformal phased array of modified box-horns is analyzed using Fresnel-Kirchhoff scalar diffraction field theory. This configuration is mainly intended as a specialized and very effective applicator for hyperthermia treatment of tumor within curved portions of human body such as abdomen, chest, neck, etc. It is proposed that the interior of the modified box-horn as well as feeding device be filled with de-ionized water to provide a better impedance match to the tissue. The contour distribution of specific absorption rate (SAR) in *x*-*y* plane, SAR distribution in *z*-direction, penetration depth, power absorption coefficient and effective field size (EFS) due to the conformal array as well as single modified box-horn are evaluated and compared at 2450 MHz. The effect of change in phase and amplitude excitation of modified box-horn of the array on SAR distribution is also investigated. Results demonstrate that conformal phased array of modified box-horns offers marked improvement in SAR distribution and penetration depth over single modified box-horn. The results obtained by the present analysis for linear array of four titanium dioxide loaded horns terminated in water are validated against published experimental results available in the literature.

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1. Introduction

[2] The primary objective of hyperthermia applicator is to raise tumor temperature in the range of 43°–50°C for an extended period, while keeping the temperature in the surrounding normal tissue below 43°C. Several array configurations using different types of applicators for hyperthermia treatment of deep-seated tumors investigated and reported in the literature by many researchers include linear array [*Gee et al.*, 1984], planar array [*Hand et al.*, 1986], hexagonal array [*Loane et al.*, 1986], circular/ring array [*Jouvie et al.*, 1986; *Paulides et al.*, 2005], cylindrical array [*Wlodarczyk et al.*, 1999], annular phased array [*Deng*, 1991] and many other array configurations using waveguides, horns, etc. For an effective hyperthermia, the applicator must possess focusing ability, be light in weight, compact and also compatible to the shape of the human body. The applicator should also have the ability to modify absorbed power distributions during use by changing the amplitude and phase of individual applicators. These requirements, put together provide a challenging list of specifications that demand innovation in applicator design beyond known conventional array configurations. The precise focusing of beams is still challenging and the conformal phased array is a prospective solution to this problem owing to the flexible contour of the array geometry, which can blend with the local body surface area and has the potential to steer the beam in the desired direction. Conformal arrays are useful for scanning over a wide range of angles, typically >±70°, whereas conventional planar arrays have substantial gain reductions and mismatch losses over wide scan angles. Conformal phased arrays offer several advantages over single element applicator. Conformal phased array applicator is capable of considerable control over the heating pattern. In addition to real time dynamic control, conformal phased array offers the possibility of focusing the energy at the tumor location, provide large penetration depth into the bio-medium and reduce undesired surface heating associated with a hyperthermia treatment.

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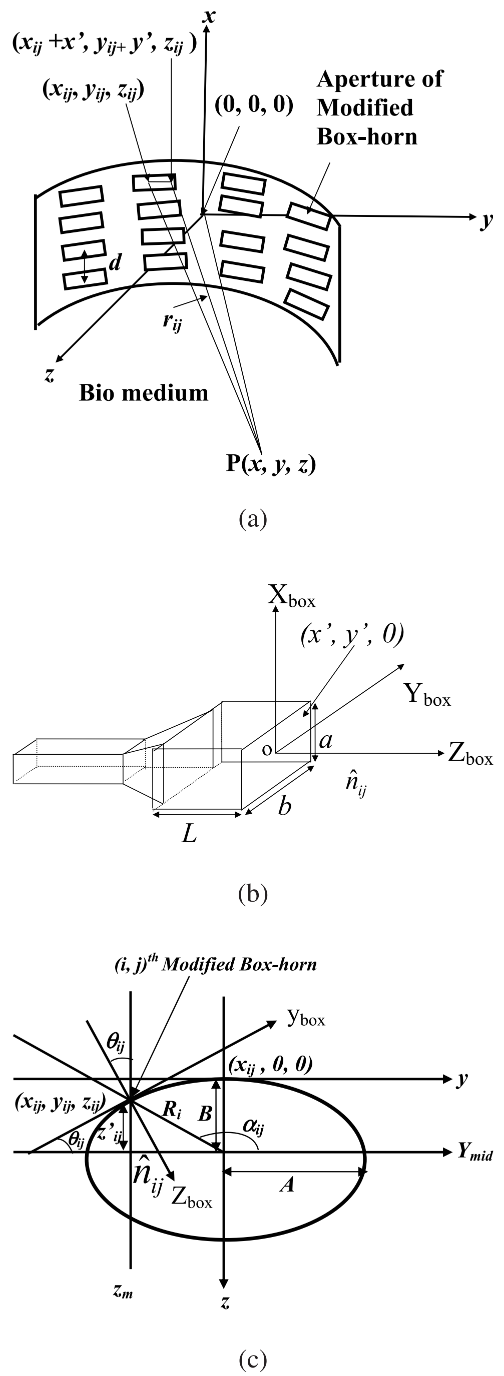


Figure 1. (a) Elliptically bent conformal array of modified box-horns. (b) Three-dimensional view of modified box-horn. (c). Angular position and angular orientation of $(i, j)^{th}$ modified box-horn of the conformal array.

[3] A novel microwave hyperthermia conformal phased array system, which differs somewhat from the conventional array applicator, is reported in this paper. The technique is based on a elliptically bent conformal phased array of water-loaded modified box-horns. The unique characteristic features of this new type of array are its compatibility with the curved surface of human body such as abdomen, chest, neck, etc. and its dynamic focusing ability. Modified box-horn is a novel and improved version of conventional box-horn [*Silver*, 1949] in which the horn exciting the box waveguide is also flared in E-plane as well as in H-plane to increase its aperture size. The field over the modified box-horn aperture is a combination of the TE_{10} and TE_{30} modes and hence field distribution over the H-plane of the aperture is a closer approximation to the uniform distribution [*Silver*, 1949] that prevents steep temperature gradient in the heating patterns. Each modified box-horn of the array is filled with de-ionized water to provide good impedance match between the horn and muscle medium, which ensures good transmission into the tissue and sufficient energy deposition at the tumor site can be achieved. Also, it reduces the dimensions of the modified box-horn which makes it suitable for array configuration. Also, feeding device (i.e., waveguide) behind the horn is filled with de-ionized water. De-ionized water is almost lossless which prevents temperature rise inside the applicator. The expression for specific absorption rate (SAR) as a function of space co-ordinates is derived for the conformal array in direct contact with a bio-medium (muscle). The fields in the bio-medium are analyzed using Fresnel-Kirchhoff scalar diffraction field theory [*Silver*, 1949]. The contours of SAR distributions, penetration depth (PD_m), power absorption coefficient (PAC_m) and effective field size (EFS) are evaluated for the conformal array and single modified box-horn at 2450 MHz. The phase and amplitude control of the elements of the array on SAR distribution are also examined. The analysis is validated by computing relative power pattern of linear focused array of four titanium dioxide loaded horns terminated in water medium and by comparing the results with the experimental results reported in [*Gee et al.*, 1984]. The theoretical results are shown to be in good agreement with experimental results available in literature [*Gee et al.*, 1984].

2. Analysis of Elliptically Bent Conformal Phased Array of Modified Box-Horns

[4] An elliptically bent conformal phased array terminated in bio-medium (muscle) is schematically illustrated in Figure 1a, and the three-dimensional view of modified box-horn is depicted in Figure 1b whereas the orientation of an element of the array is shown in Figure 1c. The bio-

medium has complex permittivity of $\varepsilon_m^* = \varepsilon - j\varepsilon'$. The narrow and broad dimensions of the aperture of the modified box-horn are denoted as a and b respectively. The length of modified box-horn along z-direction is denoted as L. In present analysis, bio-medium is considered to be elliptically shaped infinity long (along x-direction) cylinder and the aperture of modified box-horn of the array is assumed to be in direct contact and conformal with the bio-surface. In an array environment, the element pattern is affected by the mutual coupling between the elements. This effect is usually considered to be secondary and is neglected in this study, since it is investigated experimentally that coupling between adjacent waveguide elements is on the order of −30 dB, presumably low due to high medium losses [*Loane et al.*, 1986].

[5] Let the centre of $(i, j)^{th}$ modified box-horn (i.e., i^{th} modified box-horn in j^{th} elliptical arc subarray) in the conformal phased array is situated at the point (x_{ij}, y_{ij}, z_{ij}) and the coordinates of field point P be (x, y, z) with global co-ordinate system (x, y, z axes). Assume the coordinates of a point in the aperture of $(i, j)^{th}$ modified box-horn with the centre of that modified box-horn (x_{ij}, y_{ij}, z_{ij}) acting as the origin to be $(x', y', 0)$ with local co-ordinate system of box-horn (X_{box}, Y_{box}, Z_{box} axes). The local co-ordinate system of each box-horn is rotated according to its position and orientation on the elliptical cylinder with respect to global co-ordinate system. All the antenna sub-arrays considered in this study are assumed to have rotational symmetry and conformal array consists of elliptical arc subarrays stacked vertically (i.e., in x-direction). The electric-field in bio- medium due to the $(i, j)^{th}$ modified box-horn of the conformal array can be found by Fresnel-Kirchhoff scalar diffraction theory [*Silver*, 1949].

2.1. Field in Bio-Medium Due to $(i, j)^{th}$ Modified Box-Horn of Elliptically Bent Conformal Array

[6] The x-component of electric field at the aperture of the modified box-horn [*Silver*, 1949; *Terman*, 1955] is represented by

$$E(y') = (1+\Gamma_{10}) \cdot a_{10} \cos\left(\frac{\pi y'}{b}\right) e^{-j\beta_{10}L} + (1+\Gamma_{30}) \cdot a_{30} \cos\left(\frac{3\pi y'}{b}\right) e^{-j\beta_{30}L} \quad (1)$$

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

[7] The electric-field in bio-medium due to the $(i, j)^{th}$ modified box-horn of the conformal array can be found using Fresnel-Kirchhoff scalar diffraction theory [*Silver*, 1949] as follows:

$$E_{ij}(P) = \frac{1}{4\pi} \int_{area} E(y') \frac{e^{-jkr_{ij}}}{r_{ij}} \cdot \left[\left(jk + \frac{1}{r_{ij}}\right) \hat{n}_{ij} \cdot \hat{r}_{ij} + jk\, \hat{n}_{ij} \cdot \hat{s}_{ij}\right] dx' dy' \quad (2)$$

where i = 1, 2,. . ., 4 and j = 1, 2,. . ., 4, $\hat{r}_{ij}$ = the unit vector along r_{ij} from source point to the field point, $\hat{s}_{ij}$ = the unit vector normal to the equivalent wavefront at the aperture of $(i, j)^{th}$ modified box-horn due to TE_{10} and TE_{30} modes. $\hat{s}_i$ [*Silver*, 1949] can be obtained by

$$\hat{s}_{ij} = \frac{\vec{s}_{ij}}{s_{ij}} \quad (3)$$

where

$$\vec{s}_{ij} = s_x \hat{x} + s_y \hat{y} + s_z \hat{z} \quad (4)$$

$$s_x = \frac{1}{k} \frac{\partial \psi}{\partial x'} \quad (5)$$

$$s_y = \frac{1}{k} \frac{\partial \psi}{\partial y'} \quad (6)$$

$$s_z = \sqrt{1 - s_x^2 - s_y^2} \quad (7)$$

k is the complex propagation constant in bio- medium $\left(= \omega\sqrt{\mu_0 \varepsilon (1 - j\sigma_m/\omega\varepsilon)}\right)$ and ψ is equivalent phase function along the aperture of the modified box-horn due to TE_{10} and TE_{30} modes and can found by equation (1). $\hat{n}_{ij}$ is the unit vector in normal direction to the aperture of $(i, j)^{th}$ modified box-horn which is parallel to Z_{box}-axis, and is given by

$$\hat{n}_{ij} = \hat{z} \cos\theta_{ij} + \hat{y} \sin\theta_{ij} \quad (8)$$

$\hat{y}$ and $\hat{z}$ are respectively the unit vectors along y- and z-directions. ω is the angular frequency of the operating microwave. $\sigma_m (= \omega\varepsilon')$ and ε' are conductivity and imaginary part of permittivity of the bio-medium respectively. Since

$$\vec{r}_{ij} = \left\{x - \left(x_{ij} + x'\right)\right\}.\hat{x} + \left\{y - \left(y_{ij} + y'\right)\right\}.\hat{y} + \left(z - z_{ij}\right).\hat{z} \quad (9)$$

$$r_{ij} = \left[\left\{x - \left(x_{ij} + x'\right)\right\}^2 + \left\{y - \left(y_{ij} + y'\right)\right\}^2 + \left(z - z_{ij}\right)^2\right]^{1/2} \quad (10)$$

$$\hat{r}_{ij} = \frac{\vec{r}_{ij}}{r_{ij}} \quad (11)$$

Therefore,

$$\hat{n}_{ij}.\hat{r}_{ij} = \frac{\left(y - y_{ij} - y'\right).\sin\theta_{ij} + \left(z - z_{ij}\right).\cos\theta_{ij}}{r_{ij}} \quad (12)$$

After substituting for term of the integrand of equation (2) from equation (12), the electric field at point $P(x, y, z)$ due to $(i, j)^{th}$ modified box-horn can be put in simplified form as

$$E_{ij}(P) = \frac{1}{4\pi}\int_{-a/2}^{a/2}\int_{-b/2}^{b/2} E(y')\frac{e^{-jkr_{ij}}}{r_{ij}}\left(jk + \frac{1}{r_{ij}}\right) \cdot \left[\frac{\left[\left(y - y_{ij} - y'\right).\sin\theta_{ij} + \left(z - z_{ij}\right).\cos\theta_{ij}\right]}{r_{ij}} + jk\hat{n}_{ij}\cdot\hat{s}_{ij}\right]dx'dy' \quad (13)$$

Thus, with the help of equations (13), (1) and (3)–(7), we can evaluate the field at any point in the bio-medium (x, y, z) due to $(i, j)^{th}$ modified box-horn of the conformal array.

2.2. Position of $(i, j)^{th}$ Modified Box-Horn in Elliptically Bent Conformal Array

[8] The centre to centre spacing (d) between any two adjacent modified box-horns in x-direction can be chosen through the relation $d = a + \Delta d$, where Δd is adjusted for proper separation between modified box-horns. The y_{ij} and z_{ij} co-ordinates of modified box-horn can be calculated from the following relations

$$y_{ij} = p\cos\alpha_{ij} \quad (14)$$

$$z_{ij} = B - p\sin\alpha_{ij} \quad (15)$$

where

$$p = \frac{AB}{\sqrt{B^2\cos^2\alpha_{ij} + A^2\sin^2\alpha_{ij}}} \quad (16)$$

$2A$ and $2B$ are the major and minor axes of any elliptical arc subarray respectively, α_{ij} is the angular position of the i^{th} element of j^{th} subarray from y′-axis. α_{ij} can be found by the relation

$$\alpha_{ij} = \alpha_{nj} - \Delta\alpha \times (n - i) \quad (17)$$

where i = 1, 2,…m, j = 1, 2,…n. m is the number of elliptical arc subarray and n is the total number of elements in any elliptical arc subarray (for the present case n = 4). $\Delta\alpha$ is chosen according to the following relation so that any two adjacent modified box-horns along the elliptical arc subarray have proper separation.

$$\Delta\alpha \geq 2\tan^{-1}\left(\frac{b}{2B}\right) \quad (18)$$

There is equal/uniform angular distribution of the elements on the elliptical arc subarray. The angular position, α_n of the last, i.e., n^{th} element of j^{th} subarray can found by

$$\alpha_{nj} = \frac{180^\circ + \Delta\alpha}{2} + \left(\frac{n}{2} - 1\right)\cdot\Delta\alpha \quad (19)$$

2.3. Orientation of $(i, j)^{th}$ Modified Box-Horn in the Elliptically Bent Conformal Array

[9] The orientation of $(i, j)^{th}$ modified box-horn is defined by an angle θ_{ij}, which is the angle between y'-axis and tangent to the arc drawn at the central position of $(i, j)^{th}$ modified box-horn.

[10] For any elliptical arc subarray (for which x_{ij} is constant)

$$\left(\frac{y_{ij}}{A}\right)^2 + \left(\frac{z'_{ij}}{B}\right)^2 = 1 \quad (20)$$

where $z'_{ij} = B - z_{ij}$. From the geometry given in Figure 1c, it can seen that tan θ_{ij} is equal to the slope of tangent drawn at the point (x_{ij}, y_{ij}, z_{ij}) of the ellipse defined by equation (20). Thus

$$\theta_{ij} = \tan^{-1}\left(-\frac{B^2}{A^2}\frac{y_{ij}}{\left(B - z_{ij}\right)}\right) \quad (21)$$

2.4. Total Near Electric Field Due to Conformal Phased Array

[11] The total field of the array at a near-field point P(x, y, z) can be obtained by superposition of fields due to modified box-horn of the array. The total electric field amplitude at the observation point $P(x, y, z)$ due to entire array [*Gee et al.*, 1984] is given by

$$E_t(P) = \sum_j\sum_i W_{ij}E_{ij}(P) \quad (22)$$

where

$$W_{ij} = |W_{ij}|e^{j\delta_{ij}} \quad (23)$$

equal to weighting factor for $(i, j)^{th}$ modified box-horn of the elliptically bent conformal array.In order to focus the array field at a point F phase excitation of the $(i, j)^{th}$ modified box-horn must be equal to

$$\delta_{ij} = (-1)\left\{phase\ of\ E_{ij}(F)\right\} \quad (24)$$

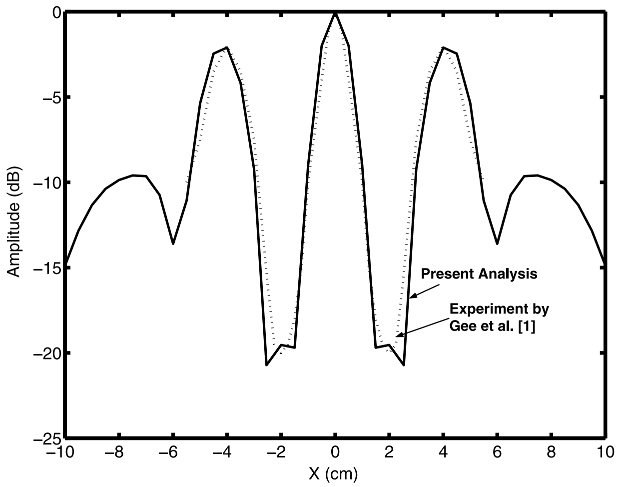


Figure 2. Relative power pattern in water for linear array of four titanium dioxide loaded TE_{10} mode pyramidal horns: Validation of the analysis against experimental results reported by *Gee et al.* [1984].

When equation (24) is used in equation (22), all the terms in the summation are added in phase at point F (and not at other observation points). A cophasal elliptically bent conformal array is one in which the phase of the excitation is so adjusted that all contributions are added in phase at a desired focal point (x, y, z). The specific absorption rate (SAR) in bio-medium can be evaluated by

$$SAR = \frac{\sigma_m |E_t(P)|^2}{2\rho_m} \tag{25}$$

where ρ_m is density of the bio-medium.

3. Validation of the Analysis

[12] The theory is validated by calculating relative power pattern of linear focused array of four titanium dioxide loaded pyramidal horns and comparing the results with the experimental results reported in [*Gee et al.*, 1984]. The horns are designed at 2450 MHz for TE_{10} mode with aperture size of 2.0 cm × 1.4 cm. The relative power pattern of four element linear array phased for focal plane z = 8.9 cm with element coordinates (cm); (−5.1, 0, 0), (−1.7, 0, 0), (1.7, 0, 0), and (5.1, 0, 0) is measured in the focal plane. The array is terminated in water with relative complex permittivity of 76.7−j12. Good agreement between the theoretical and experimental [*Gee et al.*, 1984] results is obtained as illustrated in Figure 2.

4. Design of Elliptically Bent Conformal Array of Modified Box-Horns

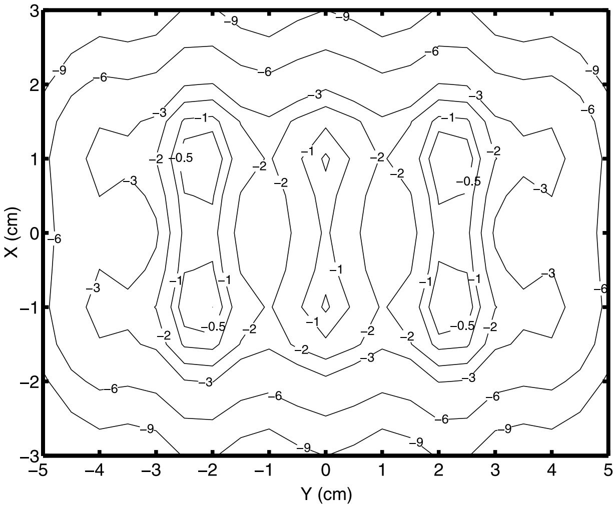
[13] For modified box-horn, the E- and H-plane flared-horn (pyramidal horn) exciting the box waveguide is designed as discussed in [*Terman*, 1955] and box waveguide is designed as per given in [*Silver*, 1949] at 2450 MHz. For brevity the design procedure is not included here. The computed dimensions of water-loaded modified box-horn at 2450 MHz are a = 1.06 cm, b = 2.23 cm, L = 1.16 cm and the flare angles of the pyramidal horn exciting the box are $\phi_H = 30°$ in H-plane and $\phi_E = 20°$ in E-plane.

[14] The permittivity of the water is taken to be 77−j12 [*ITT*, 1968]. Total sixteen modified box-horns are taken for conformal array with four elliptical arc subarrays having four modified box-horns per subarray. In present computation, practically feasible values of $2A$(= 30 cm) and $2B$(= 18 cm) are taken for abdomen region of human body. Here angular separation, $\Delta\alpha$ between two adjacent modified box-horns and spacing, d between any two adjacent modified box-horns from centre to centre in x-direction are taken equal to 14.5° and 3 mm, respectively. The four modified box-horns are situated at 68.25°, 82.75°, 97.25° and 111.75° from y_{mid}-axis on each four subarrays.

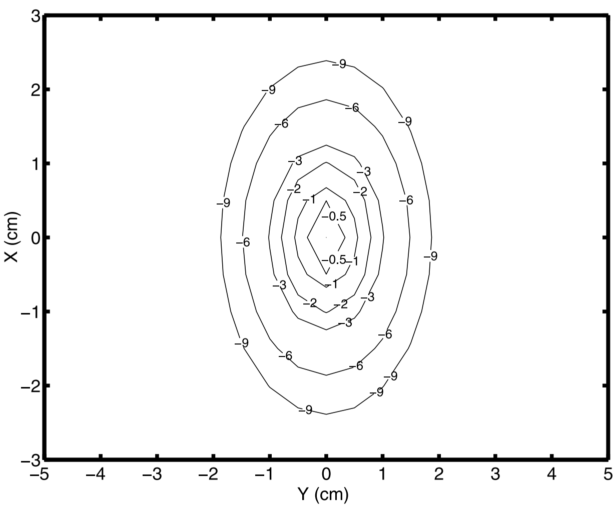
5. Numerical Results and Discussion

[15] The contour of SAR distribution in bio-medium (muscle) for elliptically bent conformal phased array of modified box-horns is computed at 2450 MHz utilizing MATLAB® software and results are presented in Figures 3–7. The properties of tumor are assumed to be identical to muscle in the present numerical computation. The complex permittivity [*Stuchly and Stuchly*, 1980] and density [*Manson et al.*, 2000] of bio-medium (muscle) are taken to be $\varepsilon^*_m = 47.5 - j13.5$ and ρ_m = 1050 Kg m^{-3} respectively in the present computation.

[16] Figure 3 illustrates the contour of relative SAR distribution (in dB) for conformal array and single modified box-horn in x-y plane at 2450 MHz. The SAR values are normalized to the maximum value of SAR in bio-medium. The effective field size (EFS) defined by the area covered by 50% (−3 dB) SAR contour, is evaluated for elliptically conformal array and single modified box-horn and the results are presented in Table 1. From Figure 3 and Table 1, it can be inferred that conformal array applicator can heat much larger area in transverse direction than single modified box-horn. Thus, conformal array can be seen to have a



(a)



(b)

Figure 3. (a) Relative SAR contour (in dB) in *x*-*y* plane at z = 2.8 cm for the conformal array. (b) Relative SAR contour (in dB) in *x*-*y* plane at z = 2.8 cm for single modified box-horn.

marked improvement over single modified box-horn in that significant levels of absorbed power are produced over a larger area beneath the array applicator.

[17] The normalized SAR distribution along z-direction for conformal array has been presented in Figure 4 along with the distribution for single modified box-horn. The penetration depth (PD_m) defined as depth where SAR value is down to 13.5 percent of the maximum in the bio- medium and power absorption coefficient

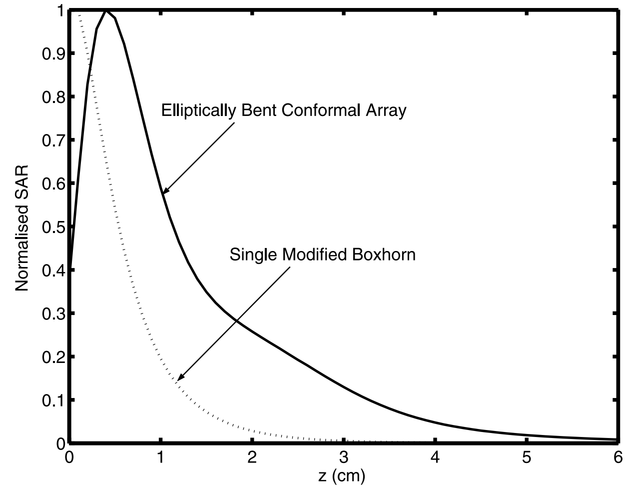


Figure 4. Normalized SAR distribution in z-direction at $x = y = 0$ cm for conformal array and single modified box-horn.

(PAC_m), which is obtained by taking inverse of penetration depth in bio- medium for conformal array and single modified box-horn are presented in Table 1. It can be seen from Figure 4 and Table 1 that conformal array can heat tumors at greater depth in comparison to the single modified box-horn applicator.

[18] Figure 5 shows the relative SAR contour (in dB) focused at the point (x = 0 cm, y = 1 cm, z = 2.8 cm) by calculating phase of excitation for modified box-horn of

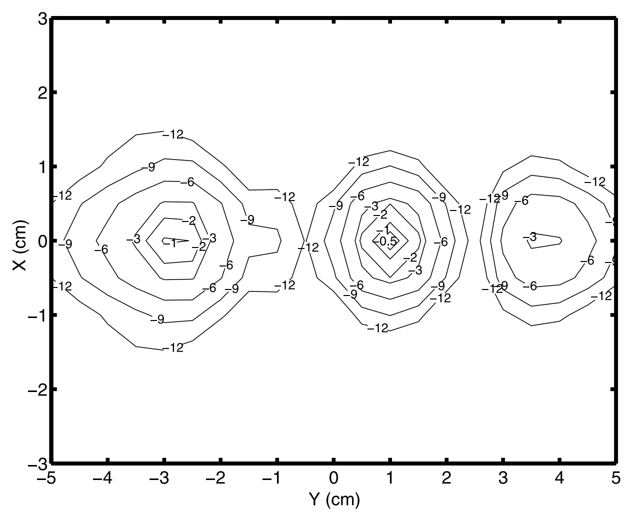


Figure 5. Relative SAR contour (in dB) in *x*-*y* plane at z = 2.8 cm for phased conformal array with different phase excitations of individual modified box-horns.

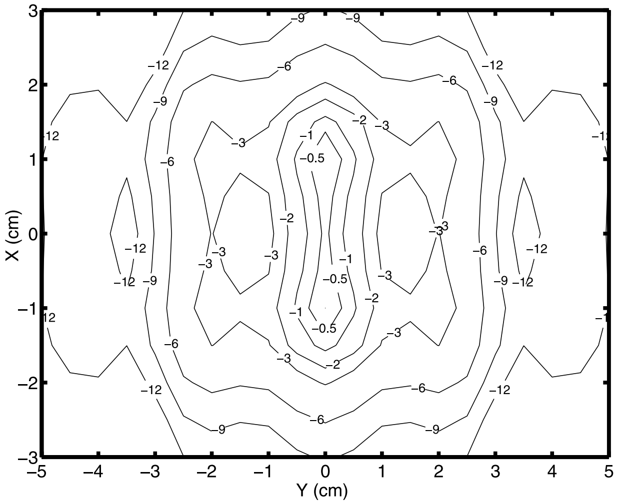


Figure 6. Relative SAR contour (in dB) in *x-y* plane at z = 2.8 cm for conformal array with different amplitude excitation of individual modified box-horn.

Table 1. Parameters of the Conformal Array and Single Modified Box-Horn at 2450 MHz

Parameters	Conformal Array	Single Modified Box-Horn
PD_m	3.2 cm	1.4 cm
PAC_m	31.25 m^{-1}	71.42 m^{-1}
EFS uniform phase and amplitude excitation	20 cm^2	3 cm^2
EFS different phase excitation	0.9 cm^2, 1.1 cm^2, 0.2 cm^2	-
EFS different amplitude excitation	14 cm^2	-
EFS different phase and amplitude excitation	1.1 cm^2	-

the array with the help of equation (18). In this case, amplitude excitation of modified box-horn of the array is kept uniform to investigate effect of phase excitation on SAR distribution. Three heating spots for focused array with appropriate phase excitation of modified box-horn are obtained with EFS equal to 0.9, 1.1 and 0.2 cm^2 in comparison to single heating spot obtained for coherent/unfocused conformal array with EFS = 20 cm^2. The larger hot spot (1.1 cm^2) is focused at the expected point (x = 0 cm, y = 1 cm, z = 2.8 cm). By comparing the focused SAR-distribution contour with unfocused SAR contour given in Figure 3a, it is concluded that by changing the phase of excitation of individual modified box-horn of the array appropriately, the hot spot can be steered to a desired location to treat deep-seated tumors in the tissue.

[19] In Figure 6, the relative SAR contour (in dB) in *x-y* plane is shown for the profile of amplitude excitation given in Table 2 for the individual modified box-horns of the conformal array. Here phase excitation of modified box-horn of the array is kept constant to observe the effect of amplitude excitation on the SAR distribution. The effective field size (EFS) is 14 cm^2 in this case, while EFS is 20 cm^2 for coherent conformal array. Thus, the shape of heating spot can be optimized by proper amplitude excitation of individual modified box-horn of the conformal array.

[20] In Figure 7, the relative SAR contour (in dB) in *x-y* plane is shown for the profile of amplitude excitation given in Table 2 for individual modified box-horns and for the phase calculated for individual modified box-horns of the conformal array with the help of equation (18) to focus the energy at the point (x = 0 cm, y = 1 cm, z = 2.8 cm). Now, EFS is 1.1 cm^2, whereas EFS is 20 cm^2 for coherent conformal array. Therefore, desired shape (EFS) of SAR distribution at tumor location (at focused

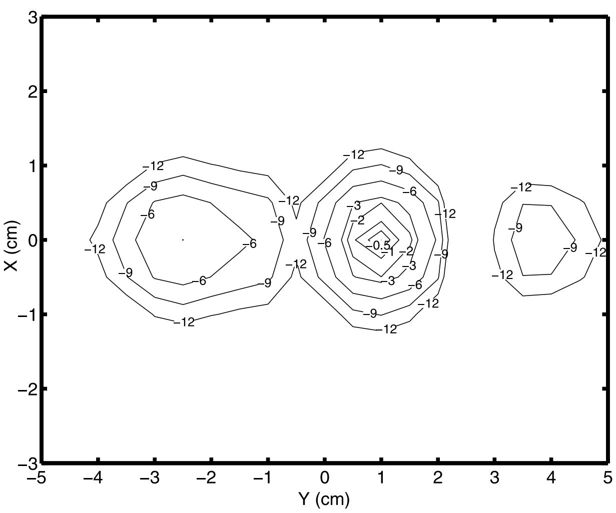


Figure 7. Relative SAR contour (in dB) in *x-y* plane at z = 2.8 cm for phased conformal array with different phase and amplitude excitations of individual modified box-horns.

Table 2. Profile of Amplitude Excitation of $(i, j)^{th}$ Modified Box-Horn of the Conformal Array

i / *j*	1	2	3	4
1	0.5	1	1	0.5
2	0.5	1	1	0.5
3	0.5	1	1	0.5
4	0.5	1	1	0.5

point) in the tissue can be obtained by appropriate amplitude and phase excitations of individual modified box-horns of the conformal array.

6. Conclusion

[21] An analytical model has been presented for SAR distribution in bio-medium (muscle) illuminated by a novel elliptically bent conformal phased array of modified box-horns. It is shown that conformal array of modified box-horns can heat larger tumor area and has higher penetration depth in comparison to single modified box-horn applicator. It is shown that by adjusting phase and amplitude excitation of modified box-horn, it is possible to heat tumors of arbitrary size selectively, i.e., heating field size can be controlled by adjusting phase and amplitude excitation of modified box-horn. Because the dielectric properties of skin are almost identical to those of muscle, the results presented here may be used for the portion of the body having negligible thickness of fat layer. We have kept some air gap between any two modified box-horns of the elliptical conformal array, so that mutual coupling is no longer affects the SAR distribution. The benefit of elliptically bent conformal array in comparison of linear array is that it is compatible or conformal to elliptical cylindrical body so that minimum radiation leakage takes place. The present theory can be utilized to develop a novel, effective and realistic elliptically bent conformal array of modified box-horns for hyperthermia treatment of cancer within the curved regions of human body, e.g., abdomen, chest, neck, etc.

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References

Deng, T. (1991), Optimization of SAR distributions in liver and lung regions irradiated by the H-horn annular phased array hyperthermia system, *IEEE Trans. Microwave Theory Tech.*, *MTT-39*(5), 852–856.

Gee, W., S.-W. Lee, N. K. Bong, C. A. Cain, R. Mittra, and R. L. Magin (1984), Focused array hyperthermia applicator: Theory and experiment, *IEEE Trans. Biomed. Eng.*, *BME-31*(1), 38–46.

Hand, J. W., J. L. Cheetham, and A. J. Hind (1986), Absorbed power distributions from coherent microwave arrays for localized hyperthermia, *IEEE Trans. Microwave Theory Tech.*, *MTT-34*(5), 484–489.

International Telephone and Telegraph Company (ITT) (1968), *Reference Data for Radio Engineers*, 5th ed., H. W. Sams, Indianapolis.

Jouvie, F., J.-C. Bolomey, and G. Gaboriaaud (1986), Discussion of capabilities of microwave phased arrays for hyperthermia treatment of neck tumors, *IEEE Trans. Microwave Theory Tech.*, *MTT-34*(5), 495–501.

Loane, J., H. Ling, B. F. Wang, and S. W. Lee (1986), Experimental investigation of a retro-focusing microwave hyperthermia applicator: Conjugate-field matching scheme, *IEEE Trans. Microwave Theory Tech.*, *MTT-34*(5), 490–494.

Manson, P. A., W. D. Hurt, T. J. D'Andra, P. Gajšek, K. L. Ryan, D. A. Nelson, K. I. Smith, and J. M. Ziriax (2000), Effect of frequency, permittivity, and voxel size on predicted specific absorption rate values in biological tissue during electromagnetic field exposure, *IEEE Trans. Microwave Theory Tech.*, *MTT-48*(11), 2050–2058.

Paulides, M. M., S. H. J. A. Vossen, A. P. M. Zwamborn, and G. C. Van Roon (2005), Theoretical investigation into the feasibility to deposit RF energy centrally in the head-and-neck region, *Int. J. Radiat. Oncol. Biol. Phys.*, *63*(2), 634–642.

Silver, S. (Ed.) (1949), *Microwave Antenna Theory and Design*, *MIT Radiat. Lab. Ser.*, vol. 12, pp. 123–174, McGraw-Hill, New York.

Stuchly, M. A., and S. S. Stuchly (1980), Dielectric properties of biological substances-Tabulated, *J. Microwave Power*, *15*(1), 19–26.

Terman, F. E. (1955), *Electronic and Radio Engineering*, 4th ed., pp. 913–916, McGraw-Hill, Kogakusha, Tokyo, Japan.

Wlodarczyk, W., J. Nadobny, P. Wust, G. Monich, P. Deuflhard, and R. Felix (1999), Systematic design of antennas for cylindrical 3D phased array hyperthermia applicator, *Proc. IEEE Int. Symp. Antennas Propag. Soc.*, *2*, 1004–1007.

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