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Slotted Waveguide Circular Arc Array Terminated in A Bio-medium for Hyperthermia

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Abstract*-A novel and effective hyperthermia applicator utilizing a circular arc phased array of longitudinal slots in narrow wall of rutile-loaded rectangular waveguide is presented and analyzed in this paper. 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, neck, chest *etc*. Each slot is excited by a coaxial line probe. The expression for electric field in bio-medium due to slotted waveguide arc array is derived utilizing Fresnel-Kirchhoff scalar diffraction field theory. The contour distribution of specific absorption rate (SAR) in x-z, x-y and y-z planes and SAR distribution in y-direction due to the arc array as direct contact applicator are evaluated at 433 MHz. The parameters such as penetration depth, power absorption coefficient, effective transverse field size (TFS), effective longitudinal field size (LFS) are obtained for the arc array. It is shown that by changing the phase and amplitude of excitation of each slot of the array, relative shape (TFS) and position of the hot spot can be changed.

***Index Terms*- Hyperthermia, Phased array, Slotted waveguide arc array, Specific absorption rate, Tumor.**

I. INTRODUCTION

The design of microwave array applicator for hyperthermia treatment of tumor within curved portion of human body such as abdomen, neck, chest *etc*. is motivated by the need to elevate the temperature throughout the tumor to the therapeutic temperature range (43^0 to 50^0 C) and selectively heat deep-seated tumors while sparing normal surface tissue. The applicator must possess focusing ability, be light in weight, compact and compatible to the shape of heating region of the 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.

A number of investigations have been carried out for several types of array configurations using different types of applicators for hyperthermia treatment of cancer. Linear array [1, 2], concentric multi-applicator phased array [3], annular phased array [4], planar array [5], circular array [6], spherical array [7] and many other array configurations using waveguides, horns *etc.* as hyperthermia applicators have been reported in the literature.

In this paper, a novel microwave hyperthermia arc array system, which differs somewhat from the above conventional array applicators, is presented. The technique is based on a circular arc array of longitudinal slots in narrow wall of rutile-loaded rectangular waveguide. The circular arc array shape is realistic and compatible with the curved outer surface of human body such as abdomen, neck, chest *etc*. The use of slots in

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waveguide has proved to be a promising means of launching high frequency radiation in bio-media. The longitudinal slots in narrow wall of rectangular waveguide are commonly called an edge slot, which possesses the key advantages of relative ease of construction, high-power handling capabilities, and broader frequency bandwidth over the broad-wall slots. The slotted waveguide arc array is assumed to be filled with the low loss dielectric material-rutile chemical name-titanium dioxide, which provides a good impedance match with bio-medium and ensures good transmission into the tissue. Also, it reduces the dimensions of the slots which make it suitable for array configuration. Slotted waveguide arc array offers the advantage of being lightweight, rugged, compact and easy to handle. The Expression for specific absorption rate (SAR) distribution is derived for the slotted waveguide arc array in direct contact with a bio-medium (muscle). SAR is a metric that quantifies the exposure of a living-being to microwave energy supplied by an applicator. The present analysis is based on Fresnel-Kirchhoff scalar diffraction field theory [8]. The contour of SAR distributions, penetration depth, power absorption coefficient, effective transverse field size, effective longitudinal field size are evaluated for the arc array and single slot at 433 MHz, one of the ISM frequencies. Each slot of the array is excited by a coaxial line probe. The effect of change in phase and amplitude excitation of each slot of the array on SAR distribution is also examined.

II. ANALYSIS OF SLOTTED WAVEGUIDE ARC ARRAY

A circular arc array of longitudinal slots in narrow wall of rutile-loaded rectangular waveguide terminated in bio-medium (muscle) is schematically illustrated in Fig. 1. The bio-medium has complex permittivity of $\varepsilon_h^* = \varepsilon - j\varepsilon'$. L and w are the length and width of the each slot respectively. In present analysis, bio-medium is considered to be extending upto infinity along positive y-direction and each slot aperture is assumed to be in direct contact with the heating surface. In present analysis, coupling from the irradiated medium back to the applicator is neglected as is mutual coupling between slots, since experimentally it is investigated that coupling between adjacent waveguide elements is on the order of -30 dB, presumably low due to high medium losses [9].

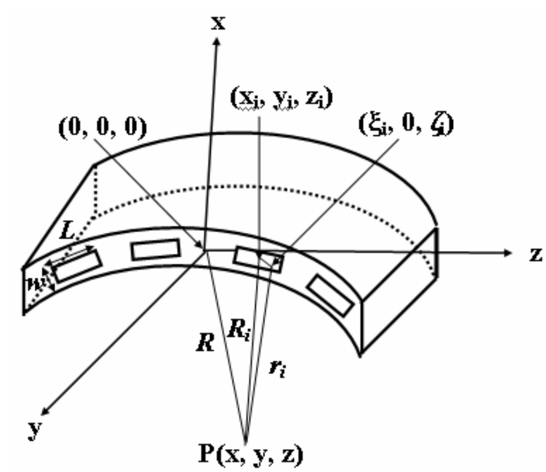

Fig. 1. Arc array of longitudinal slots in narrow wall of rutile-loaded waveguide in direct contact with bio-medium

Let centre of i^{th} slot in the array is situated at the point (x_i, y_i, z_i) and the coordinates of field point P be (x, y, z). Assume the coordinates of a point in the aperture of i^{th} slot with the centre of that slot acting as the origin to be $(\xi_i, 0, \varsigma_i)$. The electric-field in bio-medium due to the i^{th} slot of the arc array can be found by Fresnel-Kirchhoff scalar diffraction theory [8] as follows:

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$$E_i(P) = \frac{1}{4\pi}\int_{area} E(\xi_i,\varsigma_i)\frac{e^{-jk_h r_i}}{r_i}. \left[\left(jk_h + \frac{1}{r_i}\right)\hat{i}_{ni}\cdot\hat{r}_i + jk_h\,\hat{i}_{ni}\cdot\hat{s}_i\right]d\xi_i d\varsigma_i \quad (1)$$

where i=1, 2,…,4, $\hat{i}_n$=the unit vector in normal/perpendicular direction to the aperture of i^{th} slot, $\hat{r}_i$=the unit vector along r_i from source point to the field point, $\hat{s}_i$ = the unit vector normal to the wavefront at the aperture of i^{th} slot, k_h is the complex propagation constant in bio-medium $\left(=\omega\sqrt{\mu_0\varepsilon(1-j\sigma_h/\omega\varepsilon)}\right)$, $\sigma_h(=\omega\varepsilon')$ and ε' are conductivity and imaginary part of permittivity of the bio-medium respectively.

The electric field at the aperture of i^{th} slot [10] is represented by

$$E(\xi_i,\varsigma_i) = E_0 \sin k_h\left(\frac{L}{2} - |\varsigma_i|\right) \quad (2)$$

where E_0 is the maximum electric field in the slot. For nearly all aperture illuminations that concentrate energy along the normal to aperture of i^{th} slot, $\hat{i}_n.\hat{s}_i$ may be taken to be unity. The aperture plane of i^{th} slot remains perpendicular to the plane of circular arc. The conventional straight waveguide narrow wall slotted array is bent in H-plane to obtain slotted waveguide arc array. $\hat{i}_{ni}$ makes an angle θ_i angle from the –y-axis of original co-ordinate system for i^{th} slot, where θ_i is taken positive in counter clockwise direction from –y-direction. $\hat{i}_{ni}$ and θ_i are given by

$$\hat{i}_{ni} = \hat{i}_y \cos\theta_i + \hat{i}_z \sin\theta_i$$

$$\theta_i = -\sin^{-1}\left(\frac{z_i}{A}\right)$$

where A is radius of circular arc array.

Since $\vec{r}_i = \{x-(x_i+\xi_i)\}.\hat{i}_x + (y-y_i).\hat{i}_y + \{z-(z_i+\varsigma_i)\}.\hat{i}_z$

$$r_i = \sqrt{\{x-(x_i+\xi_i)\}^2 + (y-y_i)^2 + \{z-(z_i+\varsigma_i)\}^2} \quad (3)$$

$$\hat{r}_i = \frac{\vec{r}_i}{r_i} = \frac{\{x-(x_i+\xi_i)\}.\hat{i}_x + (y-y_i).\hat{i}_y + \{z-(z_i+\varsigma_i)\}.\hat{i}_z}{r_i}$$

Therefore,

$$\hat{i}_{ni}.\hat{r}_i = \frac{(y-y_i).\cos\theta + (z-z_i-\varsigma_i).\sin\theta}{r_i} \quad (4)$$

After substituting for different terms of the integrand of Eqn. (1) from Eqns. (2)-(4), the electric field at point $P(x, y, z)$ due to i^{th} slot can be put in simplified form as

$$E_i(P) = \frac{1}{4\pi}\int_{-w/2}^{w/2}\int_{-L/2}^{L/2} E(\xi_i,\varsigma_i)\frac{e^{-jk_h r_i}}{r_i} \left[\left(jk_h + \frac{1}{r_i}\right)\frac{(y-y_i)\cos\theta + (z-z_i-\varsigma_i)\sin\theta}{r_i} + jk\right] d\xi_i d\varsigma_i \quad (5)$$

The total electric field E_t at the observation point $P(x, y, z)$ due to entire array [11] is given by:

$$E_t(P) = \sum_i W_i E_i(P) \quad (6)$$

where $W_i = |W_i|e^{j\delta_i}$ (7)

= weighting factor for i^{th} slot of the arc array

In order to focus the array field at a point F we must have phase excitation of the i^{th} slot equal to

$$\delta_i = (-1)\{phase\,of\;E_i(F)\} \quad (8)$$

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When Eqn. (8) is used in Eqn. (6), all the terms in the summation are added in phase at point F (and not at other observation points).
The specific absorption rate (SAR) in bio-medium can be evaluated by

$$SAR = \frac{\sigma_h |E_t(P)|^2}{2\rho_h} \qquad (9)$$

where ρ_h is density of the bio-medium.

III. DESIGN OF SLOTTED WAVEGUIDE ARC ARRAY

Rutile-loaded rectangular waveguide EIA WR-229 with 5.8×2.9 cm^2 aperture size is chosen for slotted arc array operating at 433 MHz. The permittivity of the rutile [12] is taken to be 80–*j*0. The length of the slot may be taken as $L = \lambda_d / 2$, where λ_d is the wavelength in the rutile dielectric medium. The width *w* of the slot can be chosen from the relation $2w << \lambda_d$ and is taken as $\lambda_d / 10$. The offset of each slot from center of narrow wall is zero, *i.e.* $x_i = 0$. The z_i and y_i co-ordinates of each slot can be calculated from the relation, $z_i = A\cos\alpha_i$ and $y_i = A(1 - \sin\alpha_i)$ respectively. Typically 2*A*=30 cm for abdomen region of human body. α_i is the angle which the joining the centre of arc and the centre of i^{th} slot makes with the *z*-axis. α_i can be found by $\alpha_i = \alpha_n - \Delta\alpha \times (n - i)$, *i*= n,…2, 1. $\Delta\alpha$ can be chosen from the relation $\Delta\alpha \geq 2\tan^{-1}\left(\frac{L}{2A}\right)$, so that any two adjacent slots have proper separation. α_n can found by $\alpha_n = \frac{180^0 + \Delta\alpha}{2} + \left(\frac{n}{2} - 1\right) \cdot \Delta\alpha$. Here, *n* and $\Delta\alpha$ are taken equal to 4 and 16° respectively. The four slots are situated at 66°, 82°, 98° and 114° from *z*-axis. The computed dimensions of slots are *L*=3.87 cm and *w*=0.77 cm.

IV. NUMERICAL RESULTS AND DISCUSSION

The spatial distributions of SAR in bio-medium (muscle region) for circular arc array of longitudinal slots in narrow wall of rutile-loaded rectangular waveguide are computed at 433 MHz using MATLAB and results are presented in Figs. (2)-(6). The complex permittivity [13] and density [14] of bio-medium (muscle) are taken to be $\varepsilon_m^* = 47 - j34.9$ and $\rho_m = 1050 Kg/m^3$ respectively in the computation of SAR.
Figs. 2, 3 and 4 illustrate the contour of relative SAR distribution (in dB) for waveguide slotted arc array and single slot in *x*-*z*, *x*-*y* and *y*-*z* planes respectively at 433 MHz. The SAR values are normalized to the maximum value of SAR in bio-medium. The effective transverse field size (TFS) [15] is the area of the -3 dB iso-SAR contour on the {x, y=3.5 cm, z} bio-medium plane. The effective longitudinal field sizes, LFS_{xy} and LFS_{yz} [15] are the areas of the -3 dB iso-SAR contour measured on the {x, y, z=0} and {x=0, y, z} respectively. The evaluated transverse and longitudinal heating field size parameters (approximately) for waveguide slotted arc array and single slot are reported in Table-1. From Fig. 2 and Table-1, it is clear that slotted array applicator can heat much larger heating area in transverse direction (TFS) than single applicator. Thus, slotted array can be seen to have a marked advantage over single slot in that significant levels of absorbed power are produced over a larger area beneath the array applicator.
Also, from Figs. 3, 4 and Table-1, it is clear that slotted array applicator possesses much larger heating area in longitudinal directions (LFS_{xy}, LFS_{yz}) than single applicator.

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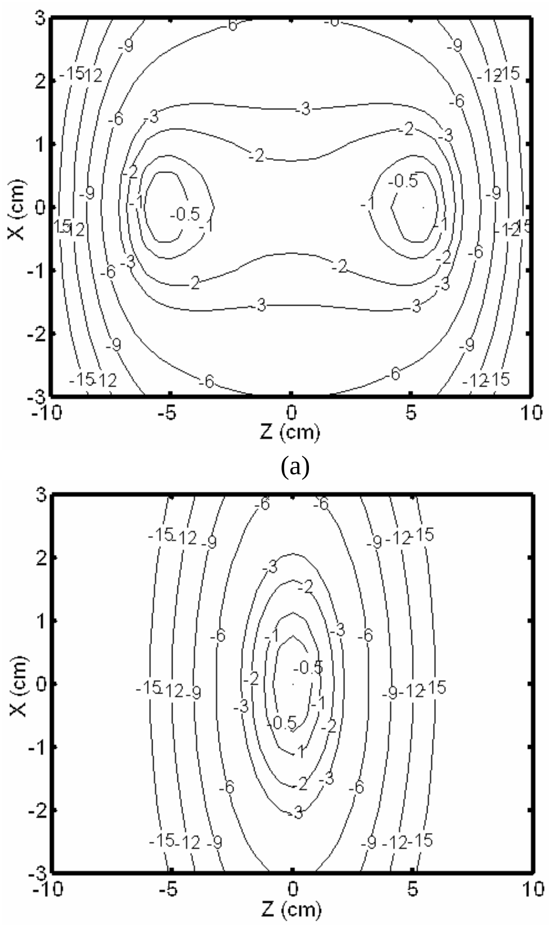

Fig. 2. Contour of relative SAR distribution (in dB) in *x-z* plane at *y*=3.5 cm for (a) slotted arc array and (b) single slot

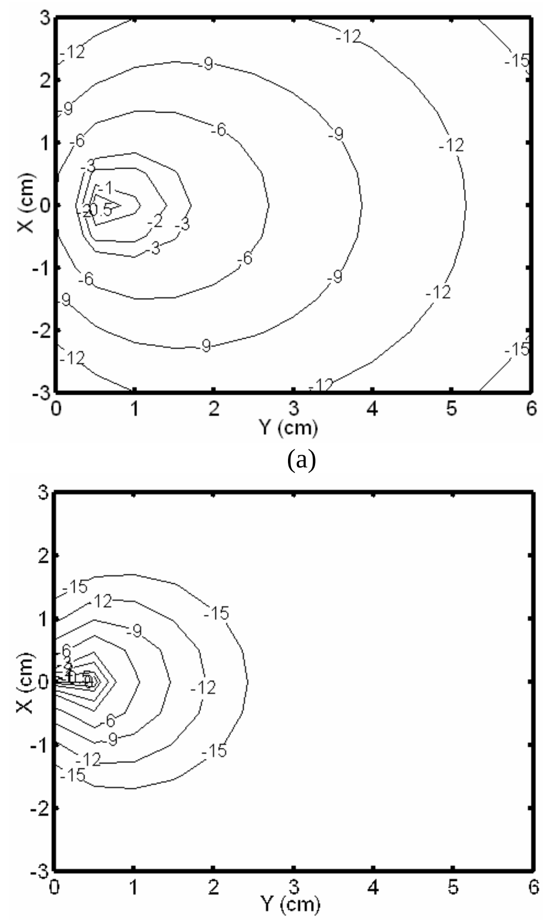

Fig. 3. Contour of relative SAR distribution (in dB) in *x-y* plane at *z*=0 cm for (a) slotted arc array and (b) single slot

Table 1: Parameters for the waveguide slotted arc array and single slot

Parameters	Waveguide Slotted Arc Array	Single Waveguide Slot
PD_h	3.8 cm	0.6 cm
PAC_h	26.3 m^{-1}	166.4 m^{-1}
TFS	30 cm^2	8 cm^2
LFS_{xy}	3 cm^2	1.5 cm^2
LFS_{yz}	1 cm^2 (4 Nos.)	1.4 cm^2 (1 No.)

Fig. 5 compares the normalized SAR distribution along *y*-direction for slotted arc array with that for single slot. The penetration depth (PD_h) defined as depth where SAR value is down to 13.5 percent of the maximum in the bio-medium and power absorption coefficient (PAC_h) which is obtained by taking inverse of penetration depth in bio-medium for slotted array and single slot are listed in Table 1. It can be inferred from Fig. 5 and Table 1 that slotted array can heat muscle at greater depth in comparison to the single slot applicator.

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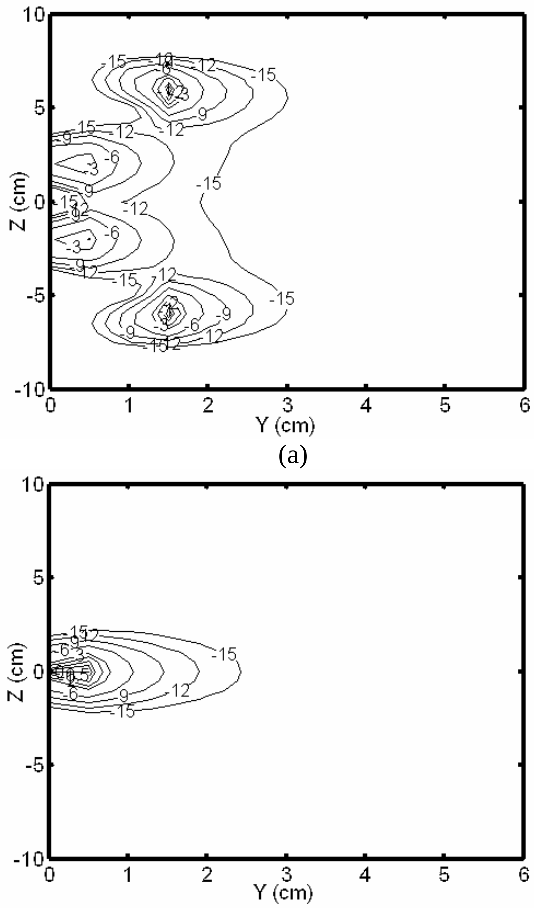

(a)

(b)

Fig. 4. Contour of relative SAR distribution (in dB) in *y*-*z* plane at *x*=0 cm for (a) slotted arc array and (b) single slot

Fig. 6(a) shows the contour of relative SAR distribution (in dB) focused [9] at the point (x=0 cm, y=3.5 cm, z=2 cm) by calculating phase of each slot of the array with the help of Eqn. (8). By comparing the focused SAR-distribution contour with unfocused/coherent SAR-distribution contour in Fig 2 (a), it is concluded that by changing the phase of each slot, the hot spot can be steered in desired direction to treat deep-seated muscle without heating the normal tissue. Two heating spots are obtained with TFS equal to 16 and 2 cm^2 in comparison to single heating spot obtained for coherent arc array (TFS=30 cm^2) with appropriate phase excitation of each slot. The large hot spot (16 cm^2) is focused at the point (x=0 cm, y=3.5 cm, z=2 cm).

The contour of relative SAR distribution (in dB) in x-z plane for the profile of amplitude excitation [0.5, 1, 1, 0.5] of the four slots of the array is shown in Fig. 6(b). Here phase excitation of each slot of the array is kept constant to observe the effect of amplitude excitation of each slot on the SAR distribution. The effective transverse field size (TFS) is 24 cm^2 in this case, while TFS is 30 cm^2 for coherent arc array.

In Fig. 6(c), the contour of relative SAR distribution (in dB) in x-z plane is shown for the profile of amplitude excitation [0.5, 1, 1, 0.5] and for the phase calculated for each slot of the array with the help of Eqn. (8) to focus at the point (x=0 cm, y=3.5 cm, z=2 cm). Now, TFS is 11 cm^2, whereas TFS is 30 cm^2 for coherent arc array. Therefore, desired shape (TFS) of SAR distribution can be obtained by appropriate amplitude and phase excitation of each slot of the array.

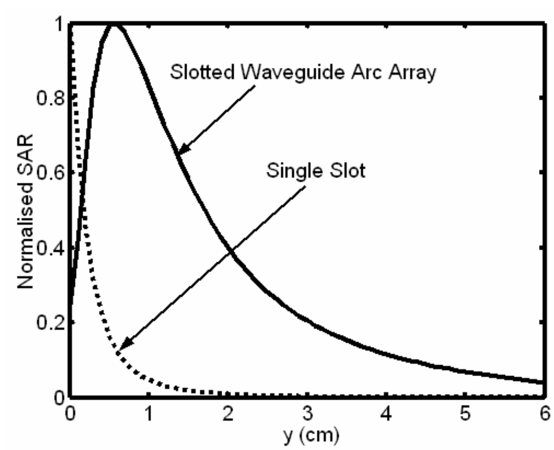

Fig. 5. Normalized SAR distribution in *y*-direction at *x*=*z*=0 cm for slotted waveguide arc array and single slot

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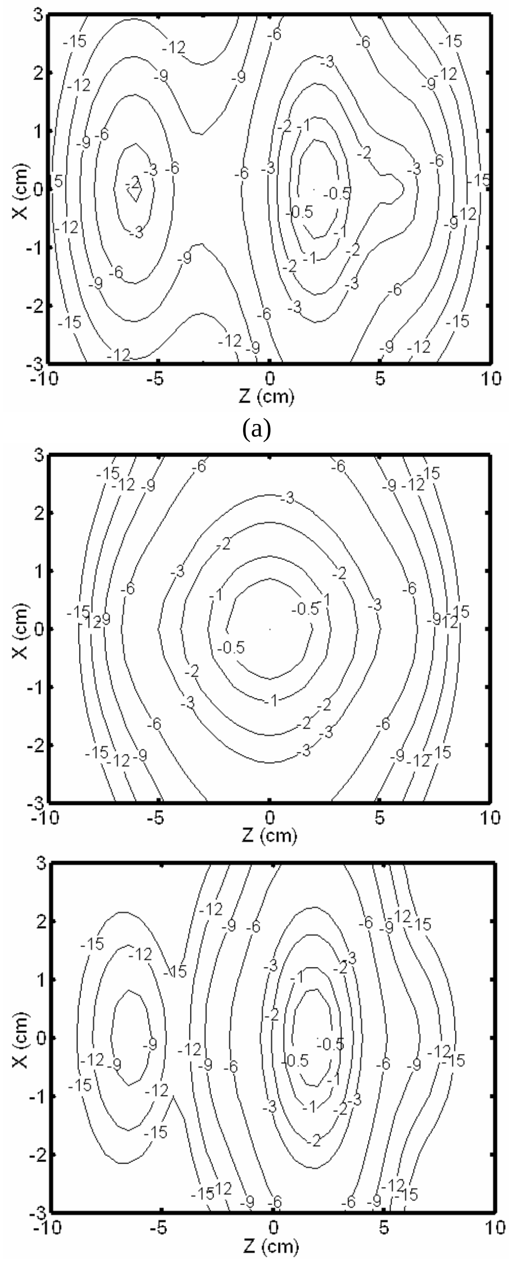

(a)

(c)

Figure 6–Contour of relative SAR distribution (in dB) in x-z plane at y=3.5 cm for slotted arc array (a) focusing at the point (x=0, y=3.5 cm, z=2.0 cm) with different phase excitation of each slot (b) with different amplitude excitation of each slot and (c) with different phase and amplitude excitation of each slot

V. CONCLUSION

An analytical solution has been presented for SAR distribution in bio-medium (muscle) illuminated by a circular arc array of longitudinal slots in narrow wall of rutile-loaded rectangular waveguide. It is shown that slotted arc array can heat larger area and has higher penetration depth in comparison to single slot applicator. It is shown that by adjusting phase and amplitude excitation of each slot, it is possible to heat tumors of arbitrary size selectively, *i.e.*, transverse and longitudinal heating field sizes can controlled by adjusting phase and amplitude excitation of each slot. 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 like abdomen, neck, chest *etc*.

The analysis and results presented in the paper may be useful for analyzing, designing and developing a novel, effective and realistic applicator for hyperthermia treatment of deep-seated cancerous growth in the curved portion of the human body, *e.g.,* abdomen, neck, chest *etc*.

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