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A Comparison between Different Schemes of Microwave Cancer Hyperthermia Treatment by Means of Left-Handed Metamaterial Lenses

Luca Leggio[1, *], Omar de Varona[2], and Ehsan Dadrasnia[2]

Abstract—In the hyperthermia therapy, multiple microwave sources can be arranged with appropriate spacing around the tissue containing tumor by using left-handed material (LHM) lenses. We employ some low loss LHM lenses schemes for an effective non-invasive microwave hyperthermia treatment of large tumors up to several centimeters of depth inside the biological tissues. Different configurations of LHM lenses are proposed and compared in order to assess the efficiency of hyperthermia treatment. High-resolution focusing of microwave radiation can be achieved by joint heating of several microwave antennas behind a conformal flat LHM lens. We show that a microwave radiation can be effectively focused in a 1.2 cm diameter tumor located within a lossy breast tissue. The results show that hyperthermia (temperature over 42°) is reached and then maintained for one hour without involving the surrounding healthy tissues. Lastly, the heating area is adjusted in both lateral and longitudinal directions changing the position of the microwave sources or selecting LHM lenses with different thickness. This approach confirms that the conformal four-lens system is more efficient to achieve microwave tumor hyperthermia than single- and double-lens schemes.

1. INTRODUCTION

Nowadays, microwave hyperthermia is considered an effective treatment for the malignant tumors [1, 2]. The microwave treatment enables in-depth tumor heating, where it is hard to access surgically. The microwave radiation is emitted from a number of antennas enclosing the body part affected by tumor. This technique requires a high precision system, in order to effectively concentrate the heating just in the tumor, without heating any surrounding healthy tissue. In the hyperthermia treatment, the temperature in cancerous area is typically raised up to over 42°C and maintained for one hour in order to destroy the tumor sufficiently, whilst in the surrounding healthy tissues the temperature is maintained below 42°C to avoid any damage. The microwave radiation emitted by an antenna that is focused by a LHM lens in a lossy biological tissue has been intensively studied [3, 4]. The experimental results prove that the concentration of heating within the biological tissue can be adjusted by moving the microwave sources with respect the LHM lenses based on tumor position. This can be improved by employing a multi-lens structure to better focus the microwave radiation inside a lossy medium (i.e., biological tissue) [3]. This concept of such a perfect LHM lens enables achieving a subwavelength focusing resolution [5], introduced by J. Pendry [6, 7]. His theory asserts that an ideal LHM lens amplifies the evanescent waves. As result, both propagating and evanescent waves contribute to the focusing of the electric field. On the other hand, in a realistic case we cannot neglect the lens losses [8]. This is due to the absorption effect that is present in any material and prevents the perfect focusing of the lens.

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* Corresponding author: Luca Leggio (luca_leggio@fastwebnet.it).
[1] COMELEC Department of Communications & Electronics, Telecom Paris Tech, Paris, France. [2] Department of Electronic Technology, University of Carlos III, Madrid, Spain.

Both the Γ-lens and four-lens systems have been proposed in [3]. A simple four-lens system ensures a better focusing resolution of microwave radiation and faster heating when the tumor is positioned in the center of the tissue. On the other hand, the Γ-lens system is more suitable in heating a tumor outside the center as it shows a good performance in terms of heating time. However, it needs an improvement in terms of focusing resolution, since the microwave excitation is geometrically asymmetric.

In this work, we study three LHM lens geometries: (i) single-lens, (ii) double-lens, and (iii) conformal four-lens. A simple double-lens system using LHM lenses which are located at the sides of the tissue has been preferred to the Γ-lens shape. Although the estimation of the heating time of tumor is out of the scope of this study, we demonstrate that a double-lens and a conformal four-lens system are more efficient in the focusing resolution of microwave radiation. Unlike a simple four-lens configuration, the conformal four-lens system proposed in this work used a triple transversal length to ensure an improved concentration and focusing of the electromagnetic power. The novelty of this work is to show that hyperthermia with a single-lens system produces a larger heating volume in longitudinal direction, leading to a low longitudinal resolution inside a biological tissue. We show that multi-lens systems are a better alternative to produce temperature concentration within the tumor compared to single-lens ones.

This study is organized into several sections. The first part of Section 2 presents the microwave focusing principle with the flat LHM lenses and a numerical model for calculating the physical properties of the media involved. The second part shows the LHM structure. Sections 3 and 4 show and compare the performances of different aforementioned schemes of LHM lenses using the graphics of temperature distribution, in order to better assess the best temperature concentration within the tumor. Besides, Section 4 gives a method to adjust the heating area depth for the case of conformal four-lens system. Section 5 finally concludes the perspective of this study.

2. BACKGROUND

2.1. Method and Theory

Figure 1 shows the principle schematic of microwave hyperthermia using a flat LHM lens. The microwave radiation emitted from the phase-center of a half-wave antenna, located in front of the LHM lens, is first focused on a spot inside the LHM lens and afterwards on point F, at a focal distance f from the interface with the lens. The point F is located in the second medium, which is the biological tissue to be treated. This lens basically uses the exotic characteristics of the LHM media with a negative effective permeability and permittivity to focus the microwave radiation [9].

In our first simulation, a half-wave antenna oriented on the y-axis is positioned in front of a LHM flat lens, whose dimensions correspond to 10 cm on the z-axis and 6 cm on both y- and x-axes.

In the subsequent simulations, several microwave sources will be applied around the biological target, i.e., the breast tissue. The LHM lens is assumed to be Drude-like dispersive, while the breast

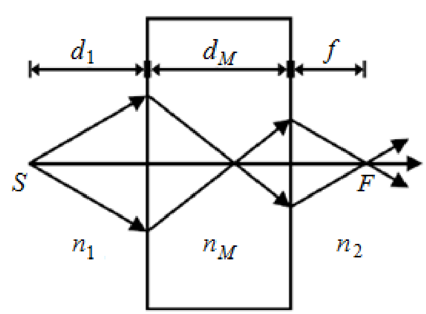


Figure 1. The principle schematic of microwave focusing using a flat LHM lens. S is the source point and F is the focal point. The distance between the source and the lens is d_1, the LHM lens length is d_M, and the focal distance is f. The refractive indices of the three different media are labeled with n_1, n_M and n_2.

tissue has Debye-like distribution [3]. To obtain the focusing within the tumor, the focal distance f is simply derived by:

$$f = |n_2/n_M|\, d_M - (n_2/n_1)\, d_1, \tag{1}$$

where n_2 is the refraction index of the biological tissue, n_M the refraction index of the lens, d_M the longitudinal thickness of the lens, n_1 the index of refraction of the first medium which can be selected by choosing a suitable coupling substance, and d_1 the distance between the source and the interface with the lens. Relation (1) can be rewritten by $f = d_M - d_1$ as $n_1 = n_2 = |n_M|$ [3].

It is achievable to focus the energy in the second medium (index of refraction n_2) as the LHM lens is explained with negative permittivity and permeability [3, 4]. To get impedance matching, a coupling liquid with the same index of refraction of the lens has been selected in module as the first medium, in which the microwave source emits the radiation. In this case, the tumor and breast sane tissue are characterized by a complex Debye-model relative permittivity $\varepsilon_{rc}(\omega)$ as follows [3]:

$$\varepsilon_{rc}(\omega) = \varepsilon_\infty - j\frac{\sigma}{\omega\varepsilon_0} + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j(\omega/\omega_p)}, \tag{2}$$

where $\varepsilon_0 = 8.854\times10^{-12}$ F/m is the relative permittivity of the vacuum, ω_p the relaxation frequency, ε_∞ the relative permittivity when $\omega \to \infty$, ε_s the relative permittivity when $\omega \to 0$, and σ the conductivity. The values used during the simulations in the CST Microwave Studio software are: $\omega_p = 157$ GHz·rad, $\varepsilon_\infty = 7$, $\varepsilon_s = 9.2$ and $\sigma = 0.15$ S/m for the breast sane tissue, while $\varepsilon_\infty = 35$, $\varepsilon_s = 50.85$, and $\sigma = 1.5$ S/m for the tumor. It should also be noted that the permeability of biological tissues can be considered with $\mu_r \approx 1$ [3]. Thus, the expression of the complex relative permittivity in (2) can be simplified as:

$$\varepsilon_{rc}(\omega) = \varepsilon_r(\omega) + \frac{\sigma_c(\omega)}{j\omega\varepsilon_0}, \tag{3}$$

where $\varepsilon_r(\omega)$ is the real part of the relative permittivity and $\sigma_c(\omega)$ the complex conductivity. There are different values of permittivity and conductivity for the breast sane tissue ($\varepsilon_r \approx 9.0$ and $\sigma_c \approx 0.4$ S/m) and the tumor ($\varepsilon_r = 50$ and $\sigma_c = 4$ S/m) found by the relation (3) at the central frequency of 6 GHz of the microwave radiation [3].

The LHM lens can be considered as an effective isotropic medium characterized by the relative permittivity ε_{rLHM} and permeability μ_{rLHM} as follows [3]:

$$\varepsilon_{rLHM}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + 2j\delta\omega}, \tag{4}$$

$$\mu_{rLHM}(\omega) = 1 - \frac{\omega_{pm}^2}{\omega^2 + 2j\delta\omega}, \tag{5}$$

where δ is the damping frequency, ω_{pe} the electrical plasma frequency, and ω_{pm} the magnetic plasma frequency. We match the LHM lens with the surrounding coupling medium and with the breast sane tissue at 6 GHz with $\omega_{pe} \approx 119.155 \cdot 10^9$ rad/s, $\omega_{pm} \approx 53.287 \cdot 10^9$ rad/s and $\delta = 1.0048 \cdot 10^8$ rad/s. Hence, the relative permittivity of LHM lens is $\varepsilon_{rLHM} \approx -9.0 + 0.004i$, the relative permeability $\mu_{rLHM} \approx -1.0 + 0.00085i$, and the index of refraction $n_{rLHM} \approx -3.0$. Table 1 shows the characteristics of the coupling liquid, LHM lens, breast tissue, and tumor at 6 GHz:

Table 1. The electromagnetic parameters of coupling liquid, the LHM lens, the breast tissue, and the tumor at 6 GHz.

Material	Index of Refraction	Relative Permittivity	Relative Permeability
Coupling Liquid	3.0	9.0	1.0
LHM Lens	-3.0	$-9.0 + 0.004j$	$-1.0 + 0.00085j$
Breast	3.0	9.0	1.0
Tumor	7.07	50.0	1.0

From (1), the focal distance f can be calculated by adjusting the thickness d_M of the LHM lens and/or the distance d_1 of the source from the interface with the LHM lens. To obtain the suitable heating of a tumor located at 3 cm of the depth inside the breast tissue (up to over 42°C), the following values are set: $d_M = 6$ cm and $d_1 = 3$ cm. In addition, different transversal lengths of the LHM lens L need to be considered in order to study their effects on the performance of hyperthermia. In the case of single- and double-lens systems, this length is set at 6 cm, while in the conformal four-lens systems $L = 18$ cm. The relative permittivity of the coupling medium in Table 1 is $\varepsilon_r = 9.0$ to reduce the reflections from the lens surface. The hyperthermia performance is characterized by a temperature distribution in the tissue calculated by means of the Pennes' bioheat equation (BHE):

$$C_p(\vec{r})\rho(\vec{r})\frac{\partial T(\vec{r})}{\partial t} = \nabla \cdot (K(\vec{r})\nabla T(\vec{r})) + A_0(\vec{r}) + Q(\vec{r}) - B(\vec{r})\left(T(\vec{r}) - T_B\right), \tag{6}$$

where Q is the electromagnetic power distribution, A_0 the metabolic heat production, B the heat exchange due to the capillary blood perfusion proportional to blood flow, C_p the specific heat capacity, ρ the tissue density, K the thermal conductivity, T_B the blood temperature, and T the position-varying temperature of the tissues. The initial temperature of the tissues (for both breast and tumor) is set at 37°C. Therefore, the bio-thermal parameters appearing in relation (6) need to be considered in the thermal solver for each tissue, as well as the general thermal parameters for both the LHM lens and the coupling medium. These thermal parameters are reported in Table 2.

Table 2. Thermal parameters of materials adopted in the simulations from Ref. [3].

Parameters	K (W/m°C)	C_p (J/(kg°C))	A_0 (W/m^3)	B (W/(m$^{3\circ}$C))	ρ (kg/m^3)
Breast	0.499	3550	480	2700	1020
Tumor	0.5641	3510	480	2700	1020
Coupling* Medium	0.025	1012	-	-	1000
LHM Lens**	401	385	-	-	8920

*for coupling medium the thermal properties of distilled water are considered.
**for LHM lenses the thermal properties of copper are considered.

2.2. LHM Structure

The LHM lenses can be built as bulk materials composed by a periodic arrangement of copper split-ring resonators (SRRs) and metallic thin wire arrays mounted on the opposite sides of FR4 printed circuit boards or fiberglass slabs [10, 11]. The metallic thin wire arrays exhibit a permittivity $\varepsilon_r < 0$ below the electric plasma frequency (ω_{pe}) in the microwave range [12]. On the other hand, an array of split-ring resonators exhibits a permeability $\mu_r < 0$ below the magnetic plasma frequency (ω_{pm}) [13]. The SRRs respond to the incident magnetic field and the thin wires respond to the incident electric field. The combination of these structures reveals an effective negative index of refraction at certain frequencies, depending on their size [14]. These constituent structures composing the LHM lenses should be much smaller that the operating wavelength, so that the entire LHM lens is "viewed" as a unique bulk medium by the microwave radiation. Unlike the positive index lenses, the overall LHM lenses do not require curved surfaces to focus EM waves. For this reason they are also called 'flat lenses'. Additionally, the negative refraction allows the LHM lenses to overcome the diffraction limit in the focusing of EM waves. On the other hand, the losses affecting both the metallic components and the substrate of the LHM lens limit the focusing resolution.

The physical implementation of the LHM lenses is illustrated in Figure 2.

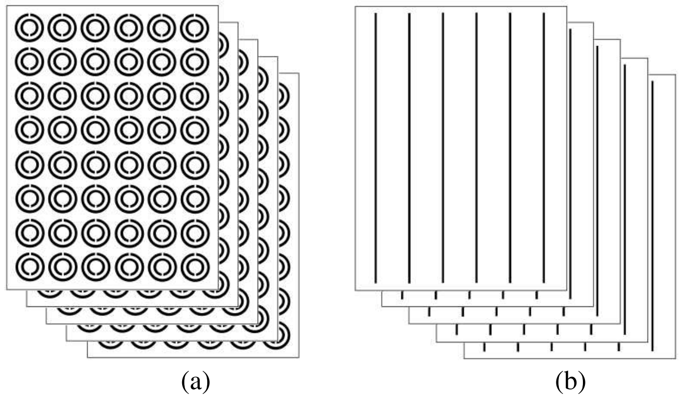


Figure 2. (a) Front side of a LHM lens consisting in arrays of SRRs disposed on dielectric slabs. (b) Back side of a LHM lens consisting in thin wires.

3. CONFIGURATIONS OF LHM LENSES

3.1. Single-LHM Lens

In the first simulation, a single LHM lens with thickness $d_M = 6\,\text{cm}$ and at a distance of 3 cm from a microwave antenna is employed to focus the radiation within a breast tumor. The antenna has been immersed in a coupling medium having the same permittivity of the breast tissue. In an ideal case [3], we consider that the medium surrounding the antenna and the LHM lens in this study have the same permittivity as the right-angle shaped breast tissue has.

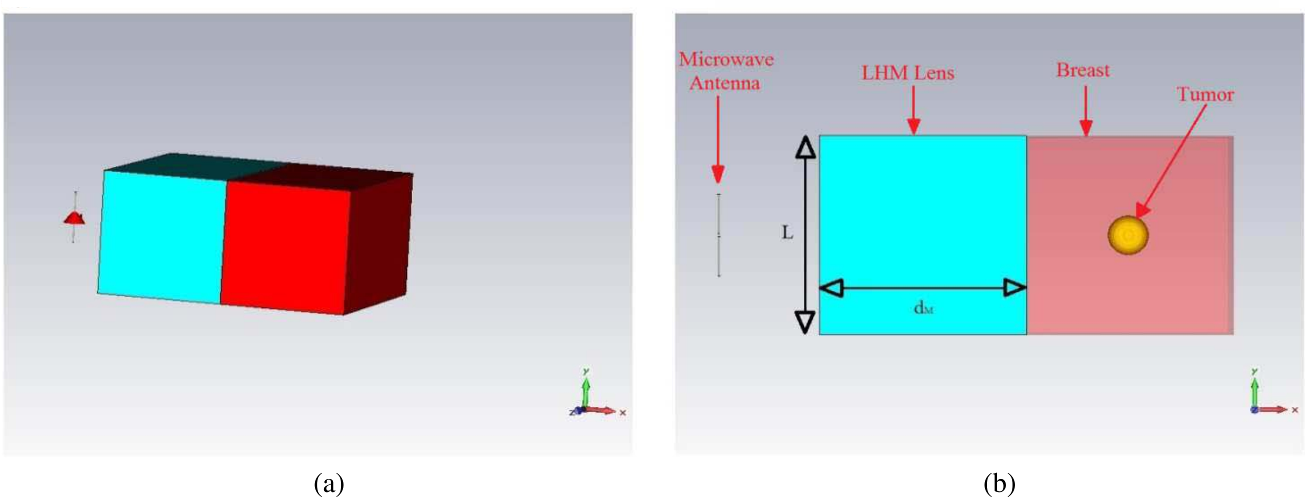


Figure 3. (a) Single-lens system for the microwave hyperthermia. The tumor is centered at (0, 0, 0) inside the breast. (b) The dimensions of the LHM lens: L is the transversal length, while d_M is the longitudinal length.

The presented biological tissues show a square shape to mimic the compression of the breast tissue in a hyperthermia treatment. The microwave antenna operates at a central frequency of 6 GHz.

The antenna center is located at ($x = -12$, $y = 0$, $z = 0$) [cf. Figure 3(a)]. The following assumption is considered to simplify the problem at the first step: neither the skin nor the fat cover the breast tissue. Figure 3(b) shows the transversal and longitudinal dimensions of the LHM lens. The longitudinal length

d_M is a key to determine the focal point within the tumor, while the transversal length L affects the focusing resolution. Practically, L has to be large enough to ensure the appropriate propagation of the beam inside the LHM lens. The position of the antenna behind the LHM lens is adjusted in according to the location of the tumor inside the breast.

3.2. Double-LHM Lens

In the second simulation, a double-LHM lens sandwich system is used to increase the number of microwave sources [cf. Figure 4(a)]. In this case, the longitudinal length of both LHM lenses is the same as that studied in Subsection 3.1, i.e., $d_M = 6\,\mathrm{cm}$ [cf. Figure 4(b)]. Also, the distance from both emitters to the LHM lenses is 3 cm as selected in the single-lens study. The two microwave antennas are centered at ($x = -12$, $y = 0$, $z = 0$) and ($x = 12$, $y = 0$, $z = 0$), respectively.

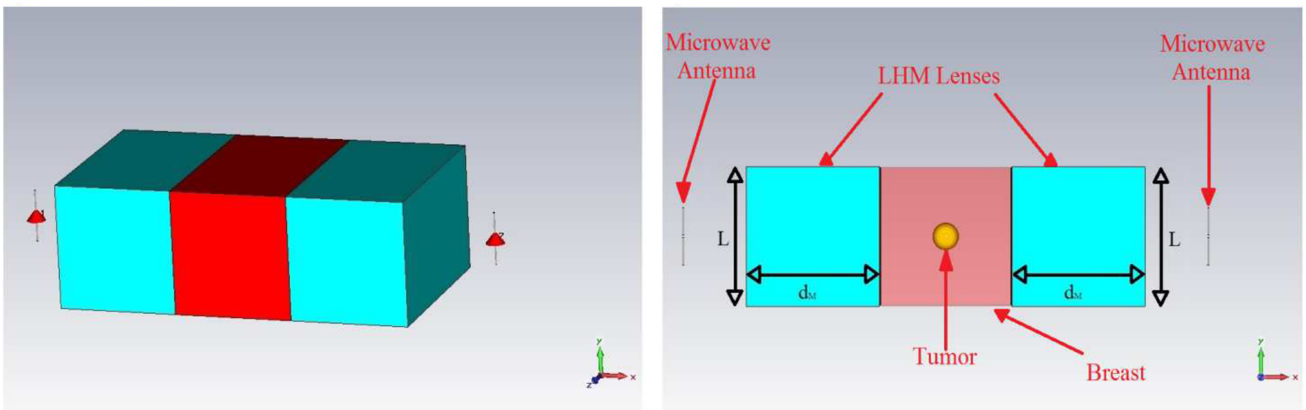


Figure 4. (a) Double-lens system for the microwave hyperthermia. The tumor is centered at (0, 0, 0) inside the tissue. (b) Dimensions of the LHM lens: L is the transversal length, while d_M is the longitudinal length.

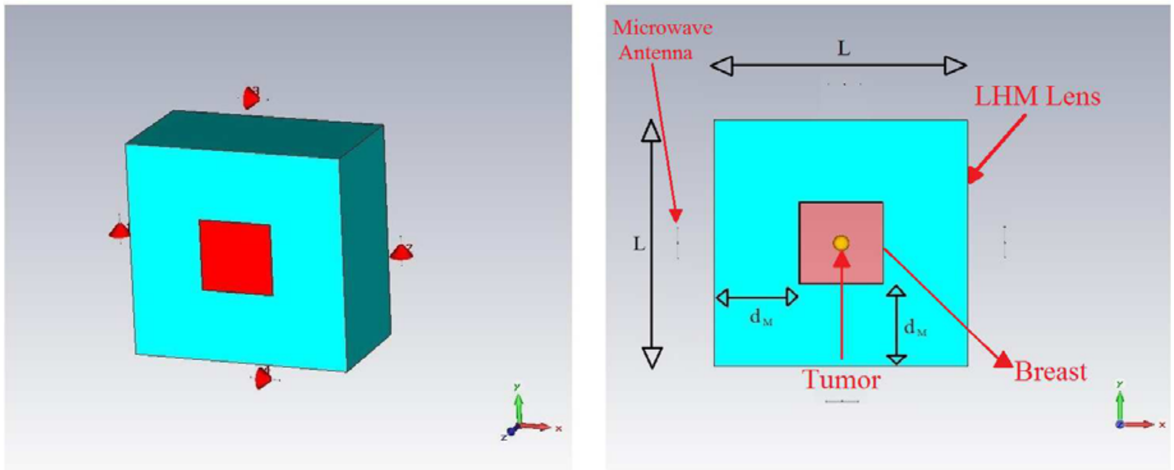
3.3. Conformal Four-LHM Lenses

In the conformal four-lens system, the longitudinal lengths and distances sources-lenses are kept equal to the previous cases. But, the transversal lengths are set to be $L = 18\,\mathrm{cm}$, creating four lenses in a "square loop". The four antennas are centered at ($x = -12$, $y = 0$, $z = 0$), ($x = 12$, $y = 0$, $z = 0$), ($x = 0$, $y = 12$, $z = 0$), and ($x = 0$, $y = -12$, $z = 0$). Figure 5(a) shows the conformal four-lens system with four microwave sources, while Figure 5(b) shows the corresponding dimensions.

4. RESULTS AND DISCUSSIONS

4.1. Standard Configuration Study

Figure 6 shows the two-dimensional (2D) electric field distributions inside the tissue on the planes XY, ZY and ZX for all above LHM configurations. It is seen that the LHM lenses are able to focus the electromagnetic radiation in a red spot within the tumor. To assess the effectiveness of hyperthermia, the temperature distribution should be maintained over 42°C only within the tumor. The temperature increases inside the tissues (from 36–37°C up to above 42°C) and is directly proportional to the electric field distribution applied from an external source. Figure 7 shows the temperature distribution on the three planes XY, ZY and ZX by applying a single lens, a double-lens and a conformal four-lens system. To ensure the destruction of cancerous cells, in this simulation, the temperature increases and then is maintained over 42°C for one hour. All temperature distributions within the tumor, in Figure 7, tend



(a) (b)

Figure 5. (a) Conformal four-lens system for microwave hyperthermia. The tumor is centered at (0, 0, 0) inside the tissue. (b) Dimensions of the LHM lens: L is the transversal length, while d_M is the longitudinal length.

to have an elliptical shape. This does not prove whether the hyperthermia is achieved only within the tumor or even in the surrounding tissue. This effect in details can be seen in Figures 8–10 by studying the represented temperature distributions in each axis. These elliptical temperature distributions on the three planes have a Gaussian shape as the temperature moves to the focal points. The single-lens system causes a remarkable aberration that can be noticed in the temperature concentration around the tumor region within both XY and XZ planes. Because of using only one electromagnetic source that produces an imbalance in the temperature distribution, the spot size is elongated [cf. Figures 7(a) and 8]. In this study, the tumor location is between −0.6 cm and 0.6 cm inside the breast tissue. Figure 8 shows that the simple-lens configuration has a high lateral resolution and a low longitudinal resolution of temperature focusing. This can be validated by the results in Refs. [15]. Thus, the number of microwave sources and the corresponding LHM lenses need to be increased. The hyperthermia concentration (over 42°C) inside the cancer tissue covers approximately 4.76 cm (between −3.0 and 1.76 cm) on x-axis, which is larger than the diameter of the tumor (i.e., 1.2 cm) [cf. Figure 8]. This value should be less than 1.2 cm. The maximum temperature can be reached up to ~ 46°C within the tumor, as shown in Figure 8, even though the heating zone exceeds the tumor diameter and affects the healthy breast. The focusing resolution is perfectly symmetrical on both y-axis (1.14 cm) and z-axis (0.92 cm).

Gong et al. have reported two flat LHM lenses, having a triple transversal length, in a Γ-shaped configuration, in order to improve the focusing resolution within the tumor [3]. They have also demonstrated that the focusing shape is still elongated in such a system, which is undesirable in the hyperthermia treatment because can affect the surrounding tissues, even though it was improved compared to the single lens-case.

However, in this study, the double-lens configuration consisting of two lenses located at the opposite sides of the tissue improves the focusing resolution and the temperature concentration within the tumor. Figure 9 shows the hyperthermia concentration inside the tumor that covers approximately 1.13 cm on x-axis only within the tumor and is not perfectly Gaussian-shaped. The focusing resolution is perfectly symmetrical on both y-axis (0.89 cm) and z-axis (0.69 cm).

Table 3 shows the focusing resolutions of the single-, double- and conformal four-lens systems studied [cf. Figures 8–10]. The aim of our study is to assess the focusing resolution improvement by adding lenses to the system. The numbers in parenthesis in columns 3 and 4 of Table 3 present the percentages of improvement of double- and conformal four-lens systems in comparison with the single-lens configuration. This enhancement of focusing resolution along the different axes is because the transversal length of the lenses is three times larger. This reason aims to better collect the heating

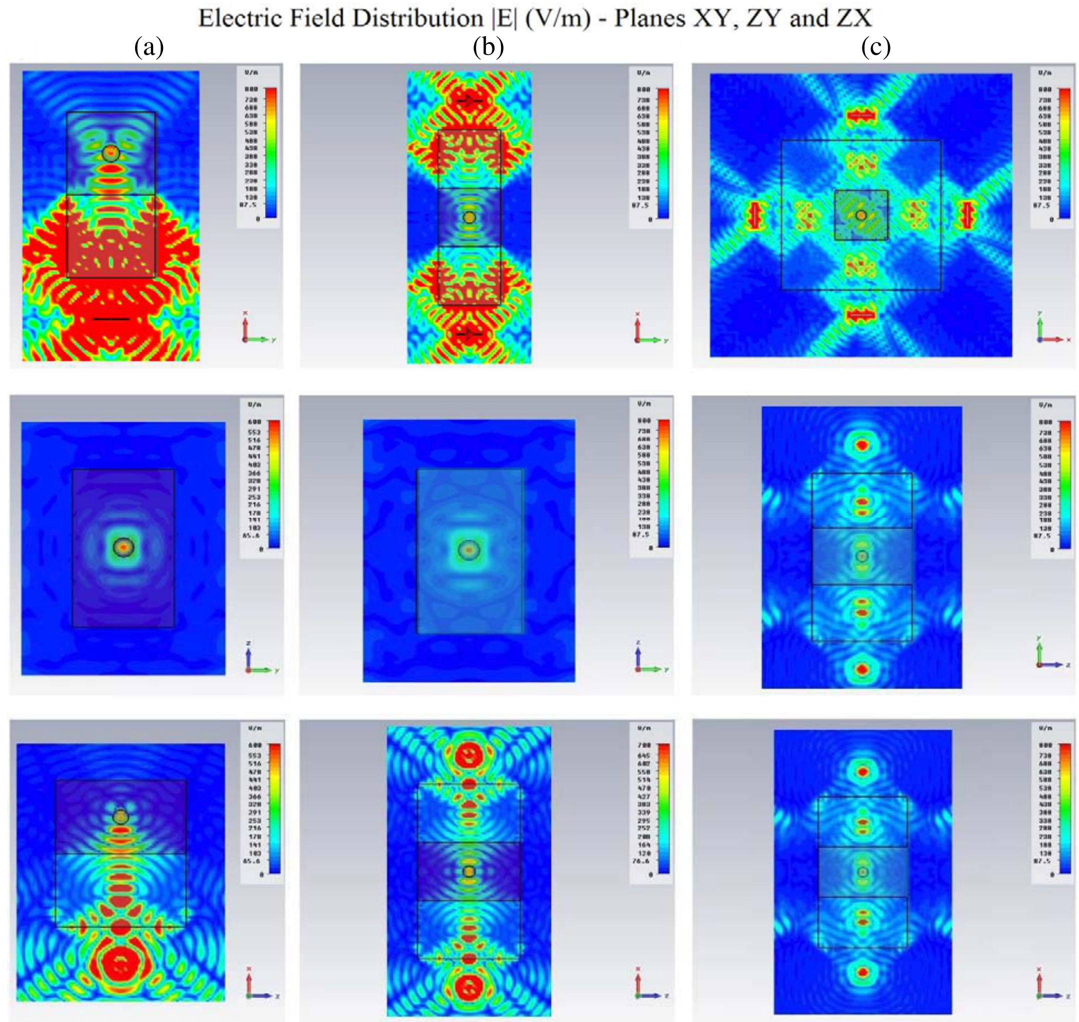


Figure 6. Focusing of electric field on the three planes XY, ZY and ZX (Absolute Values).

Table 3. Focusing resolutions of different configurations of LHM lens systems presented in this paper. The values in parenthesis in columns 3 and 4 present the percentage of improvement of the double- and conformal four-lenses in comparison with the single-lens configuration in 2^{nd} column.

Focusing resolution (cm)	Single-lens	Double-lens	Conformal four-lens
Along x-axis	4.76	1.13 (76.26%)	0.87 (81.72%)
Along y-axis	1.14	0.89 (21.93%)	0.87 (23.68%)
Along z-axis	0.92	0.69 (25%)	0.61 (33.7%)

that avoids the field diffraction from the edges shown in Figures 6(a) and (b). On the other hand, a conformal geometry will be more practicable in a realistic employment. The conformal four-lens configuration shown in Figure 7(c) gives a good focusing resolution, which is approximately 0.86 cm on both x-/y- axis and 0.61 cm on z-axis. They perfectly show a symmetric shape within the tumor (cf. Figure 10). In contrast, the Γ-lens system has shown a 73–74% improvement in the longitudinal resolution and about 14–18% improvement in the lateral resolution compared to the single-lens case, in

Ref. [3]. Instead, the four-lens system has proved improvements of 76–77% and 24–27%, respectively. In Figures 8–10, the temperature distribution on each axis is shown: The violet lines indicate the part of the tissue in which hyperthermia effect (over 42°C) occurs.

The results show that both the double-lens and four-lens configurations ensure a heating over 42°C only within the tumor. However, the conformal four-lens system allows a better temperature concentration within the tumor because the hyperthermia affects a smaller area. Thus, the conformal four-lens system appears to be the best choice. Contrarily, the single lens system is proved to be not adequate to achieve good hyperthermia performances due to a poor longitudinal resolution.

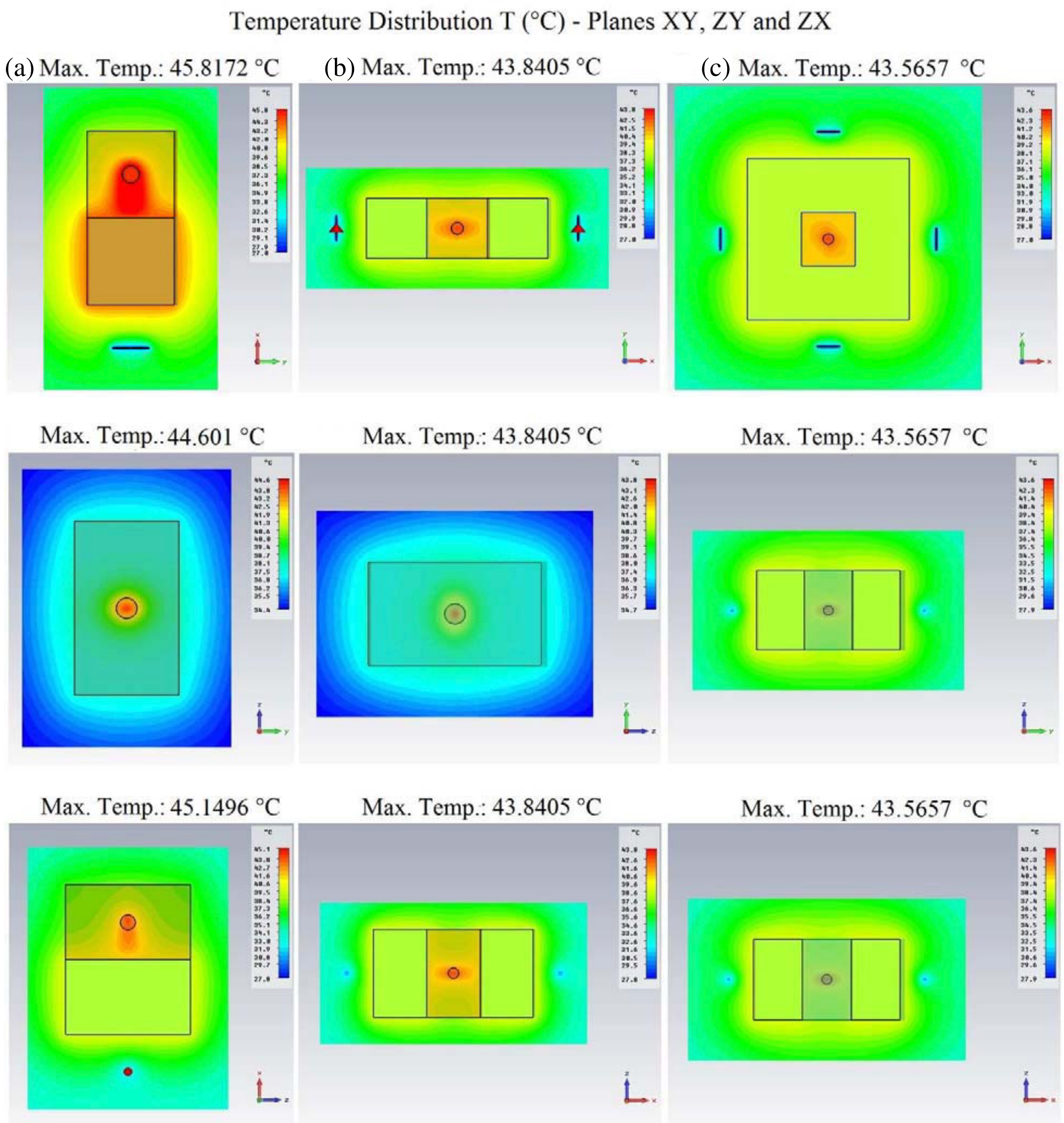


Figure 7. Temperature distribution inside the breast tissue on the three planes XY, ZY and ZX (absolute values), for each lens system: a) Single-lens system, b) Double-lens system, c) Conformal four-lens system. The resolution of the focusing: (a) for a single-lens suffers from a strong aberration on both the planes XY and ZX, (b) for a double-lens system and (c) for a conformal four-lens system presents an elliptical shape.

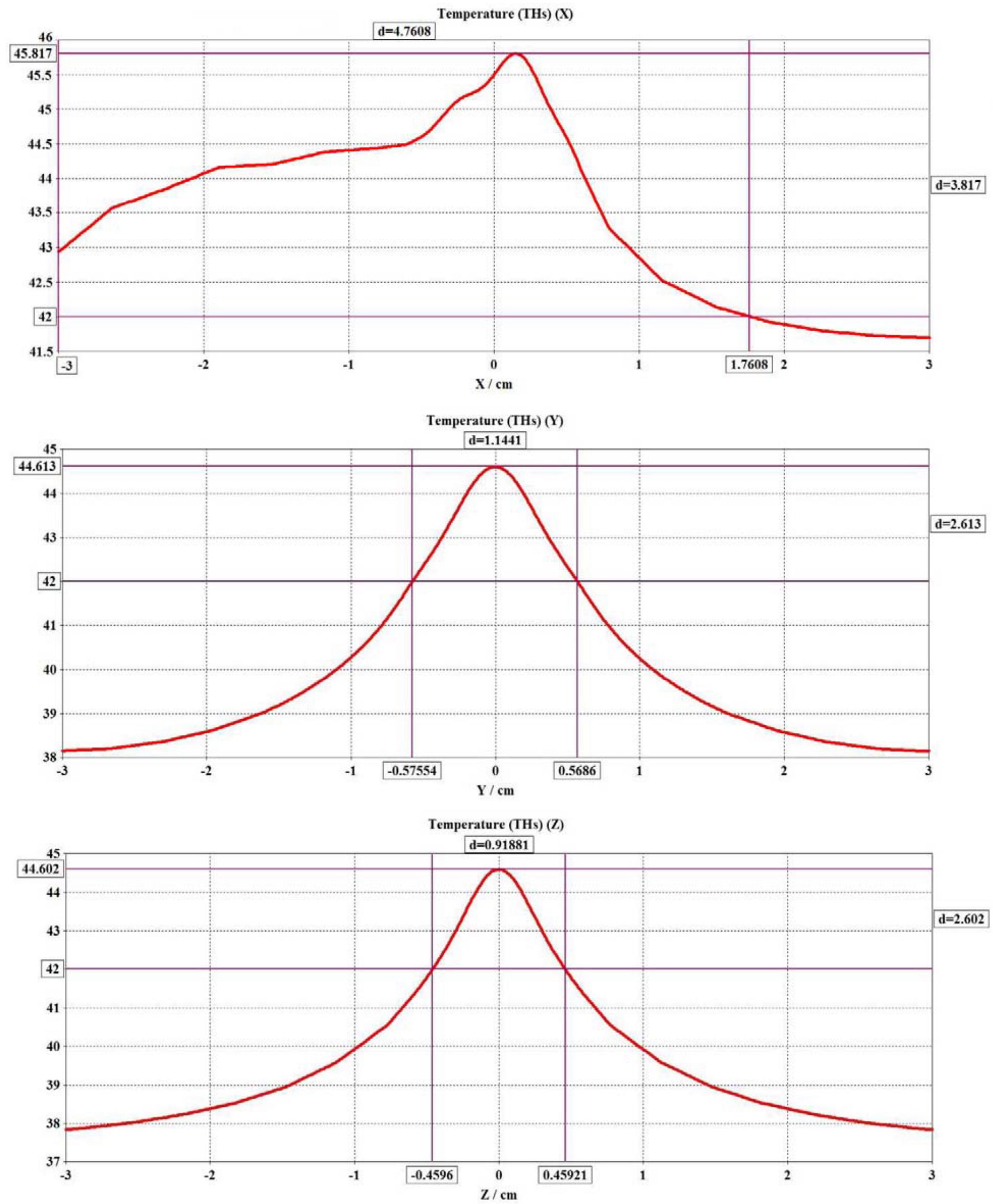


Figure 8. Single-lens system: temperature distribution inside the breast tissue on the x-, y-, and z-axes, respectively.

4.2. Particular Configuration Study

In contrast with the previous section, we examine the case in which the tumor is not centered at (0, 0, 0), and the distances of tissue from the lenses are not equal. We apply this variation to the conformal four-lens system as it has shown higher resolution performance (cf. Table 3) than other configurations. The tumor is located at (1, 0, 0) as shown in Figure 11 and is positioned at 4 cm of distance from the left-side lens and 2 cm from the right-side lens. To study the performance of the asymmetric conformal four-lens system, we consider two different changes: i) the longitudinal length of the lenses [cf. Figure 11(a)], and ii) the positions of the antennas according to the relation (1) [cf. Figure 11(b)]. In the first case, as shown in Figure 11(a), the left-side lens is set with $d_M = 7\,\text{cm}$ and the right-side lens with $d_M = 5\,\text{cm}$.

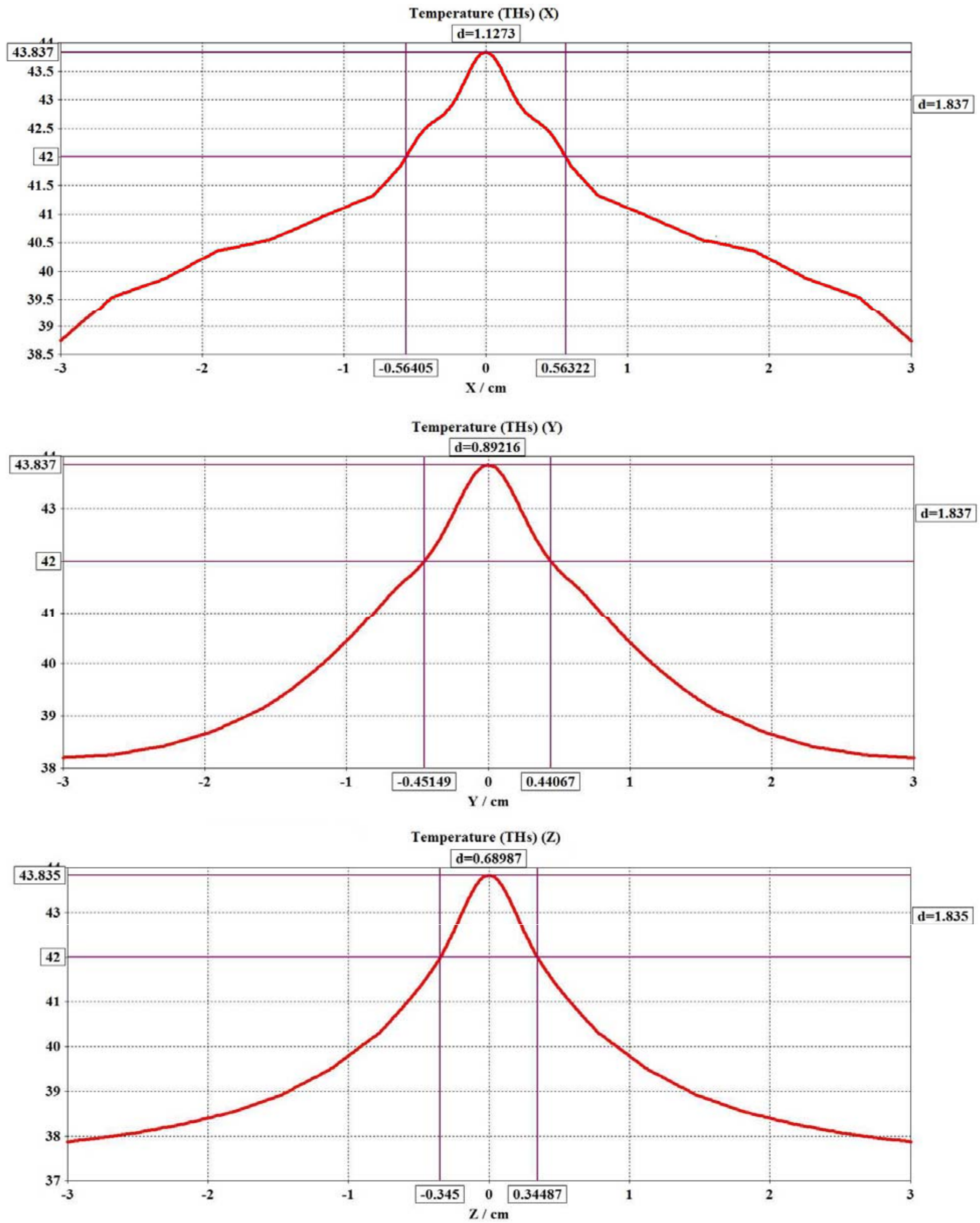


Figure 9. Double-lens system: temperature distribution inside the breast tissue on the x-, y-, and z-axes, respectively.

The distances of lenses from the corresponding antennas are maintained at 3 cm. The four antennas are centered at ($x = -13$, $y = 0$, $z = 0$), ($x = 11$, $y = 0$, $z = 0$), ($x = 0$, $y = 12$, $z = 0$), and ($x = 0$, $y = -12$, $y = 0$). In the second case, as shown in Figure 10(b), the longitudinal length of each lens is set at 6 cm. The distances of lateral lenses from the corresponding antennas are 2 cm and 4 cm, respectively.

Figure 12 shows the temperature distribution on the three planes XY, ZY and ZX by changing i) the longitudinal lengths of the left-side and the right-side lenses, ii) the distances lenses-antennas.

Figure 13 shows the corresponding temperature distributions on each axis for both cases i and ii. Both cases are efficient to achieve good hyperthermia performance because only the tumor is

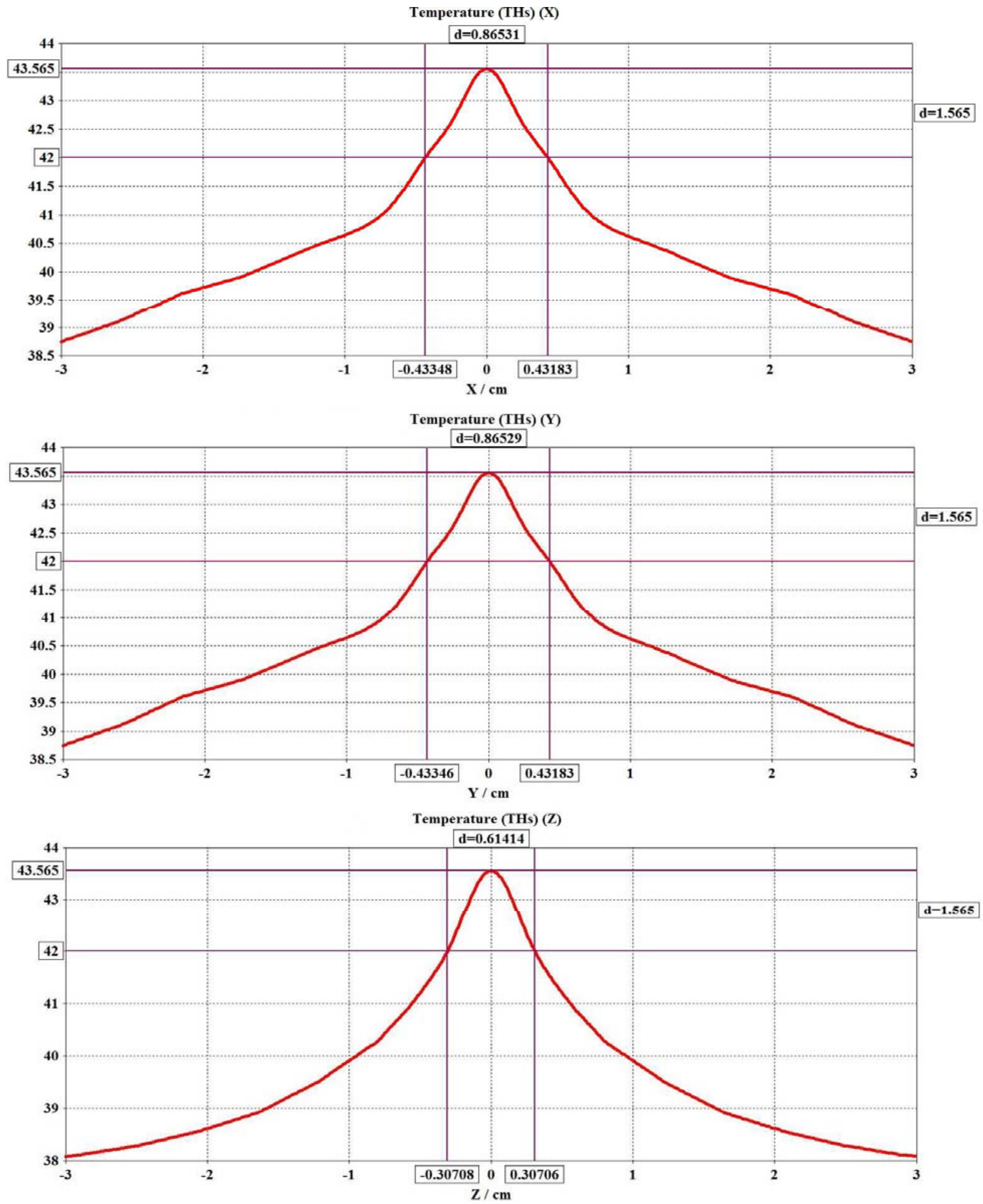


Figure 10. Conformal four-lens system: temperature distribution inside the breast tissue on the x-, y-, and z-axes, respectively.

involved. On the other hand, the configuration shown in Figure 11(b) offers a more effective temperature concentration within a smaller tumor because the hyperthermia affects a smaller area. The focusing resolution of the first configuration (i) is approximately 0.68 cm on x-axis, 0.63 cm on y-axis, and 0.46 cm on z-axis, while the focusing resolution of the second configuration (ii) is approximately 0.52 cm on x-axis, 0.48 cm on y-axis, and 0.33 cm on z-axis. As the focusing resolution performances of the two configurations are approximately equal, it would be more logical and easier to change the position of the sources in (ii).

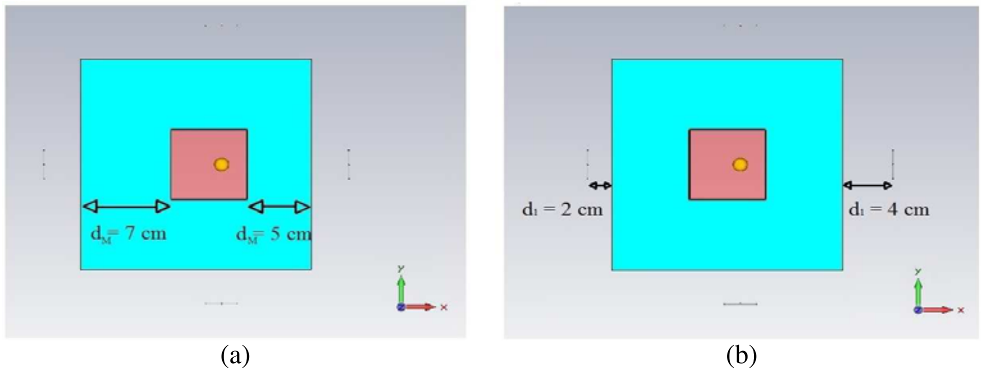


Figure 11. Conformal four-lens systems in which the left-side and the right-side lenses have: (a) different lengths, (b) different distances from the corresponding antennas.

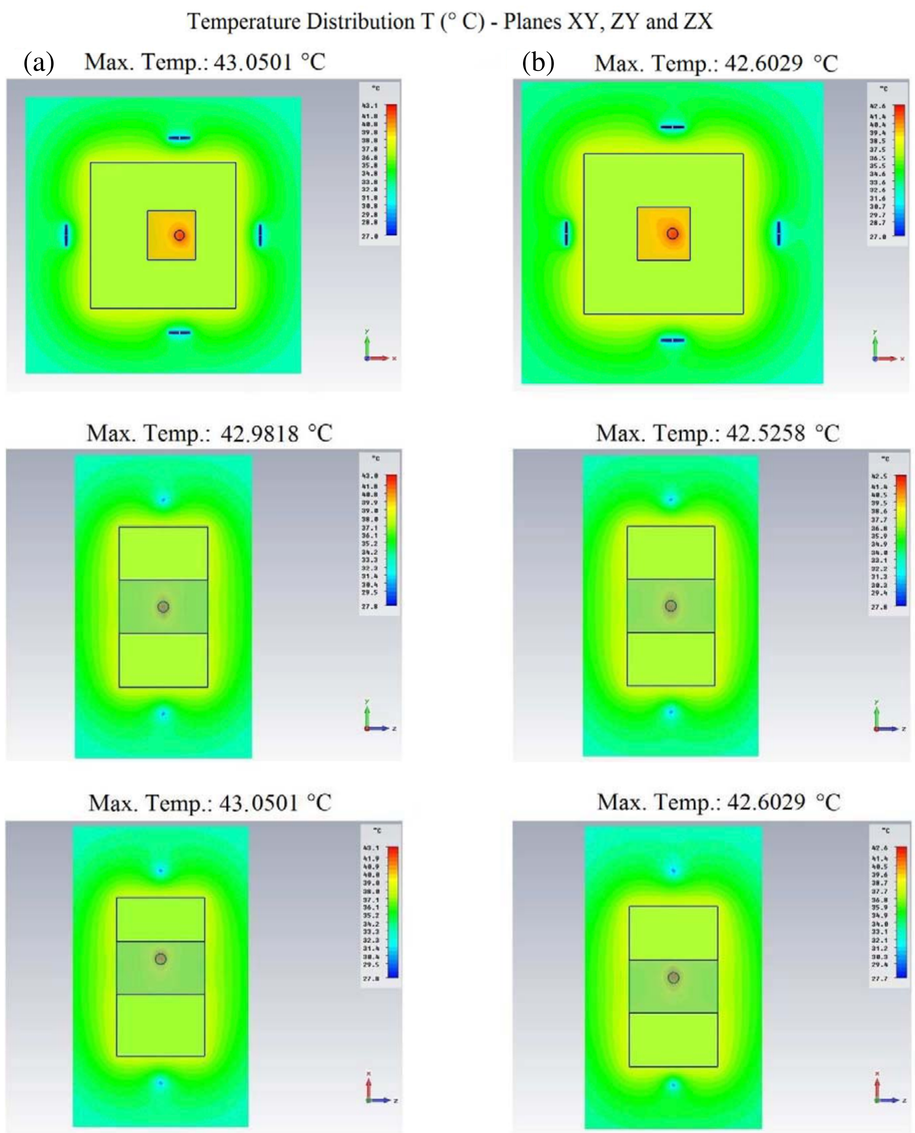


Figure 12. Temperature distribution for the two configurations: (a) the lenses have different lengths, (b) the distances between antennas and lenses are different.

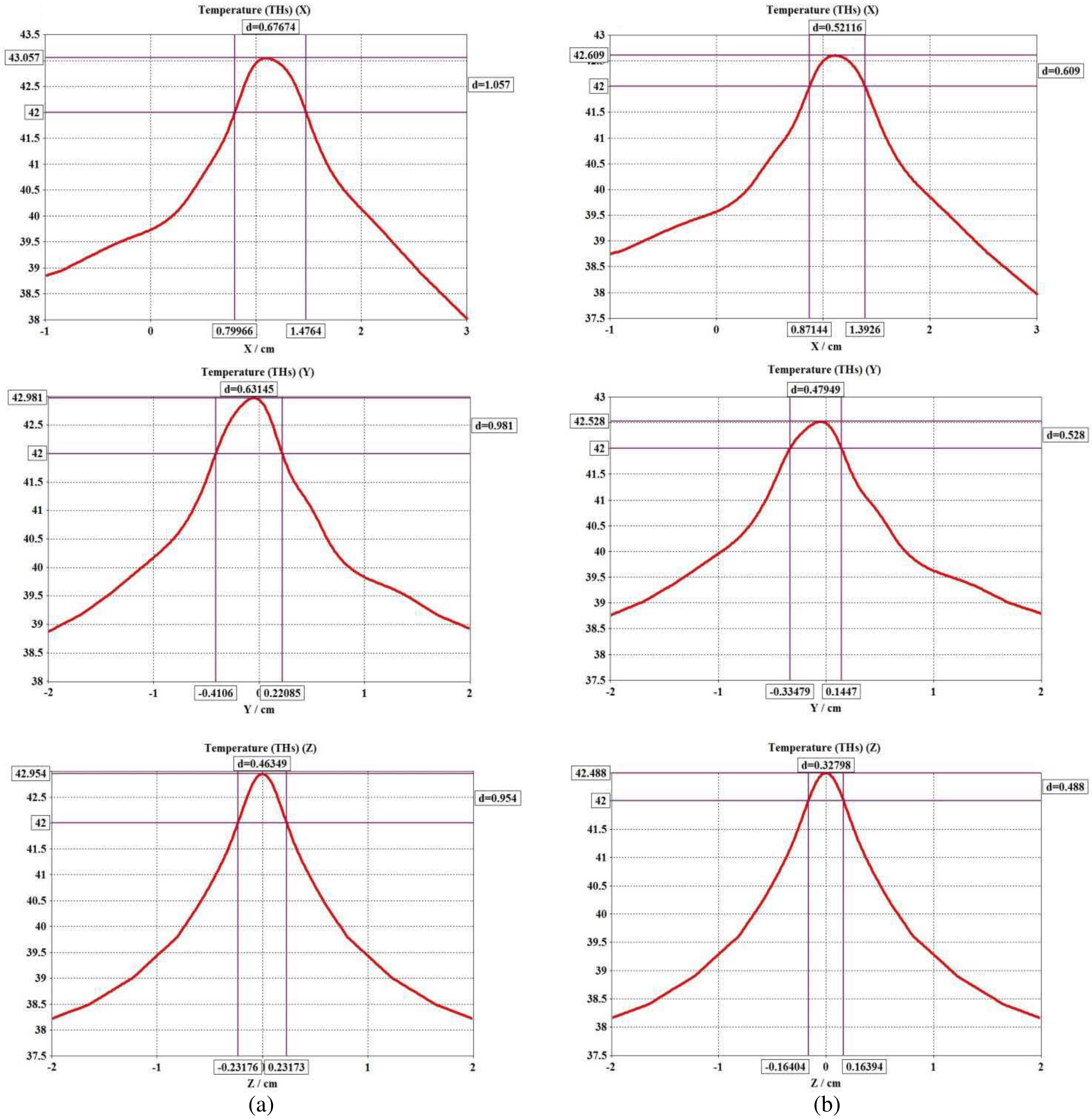


Figure 13. Temperature distribution inside the breast on all the axes, by changing: a) the longitudinal lengths of left-side and right-side lenses, b) the distances lenses-antennas. In both the cases, the hyperthermia occurs only within the tumor, but a better heating concentration occurs with the configuration (b).

5. CONCLUSIONS

In this work, we have shown a potential biomedical application of different shapes of LHM lenses, which can be used to focus the microwave radiation within a tissue affected by cancer. We have designed the single-, double-, and conformal-four lens systems by comparing their temperature concentration performances inside the tumor. Using the Drude and Debye models, we have studied the physical parameters of relative permittivity and permeability. The lens has been designed to match the refraction index of the coupling medium with the biological tissue.

The results have demonstrated that the conformal four-lens system provides a better focusing resolution than single- and double-lens systems, permitting its application with no risk of damaging around the tissue. It has been shown that the hyperthermia area within the tissue can be carefully adjusted by moving the antennas or by changing the thickness of the LHM lenses based on the tumor position. Even though the simulations performed in this work have taken into account an ideal case, some real characteristics can be considered to improve the obtained results in a realistic model. As future lines of research for the bioengineering applications, we consider a multi-layer environment inside the tissues. Different shapes of lens systems need to be studied and implemented with the human body shapes, which are typically elliptical or cylindrical.

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