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Breast Cancer Hyperthermia Treatment Based on Slotted Patch Antenna at 2.45 GHz

Mussa Elsaadi[1], Rema Hamad[2]

[1]Department of Electronic and Electrical Engineering, Tobruk University, Tobruk, Libya
[2]Department of Electronic and Electrical Engineering, University of Omar Al-Mukhtar, Beida, Libya
Email: mussa.elsaadi@tu.edu.ly

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Abstract

The present work proposed a simple model for breast cancer hyperthermia treatment at 2.45 GHz. The proposed model involves nine-element antennas alongside a numerical breast comprising multiple tumors. Using a coupled EM-Thermal simulation in the CST suite, the simulated results for a single antenna showed a reflection coefficient (S_{11}) better than −47 dB and demonstrated a bandwidth of 78 MHz. The specific absorption rate (SAR) as a function of input powers was examined inside the breast tissues, where it exhibited a promising performance higher than 3 W/kg at the tumor volume when the applied power was at a reasonable level of 1.5 W whereas it was well attained under the recommend IEEE level of 1.6 W/kg through the surrounded health tissues. Taking into consideration nine-element antennas covering the breast containing two different located tumors, the maximum temperature as a function of treatment time was presented at which a resulting temperature of 43˚C was obtainable within 10 minutes, favored for hyperthermia purposes. Considering the maximum power level of 1.5 W, the potential use of applying three-element antennas, simultaneously with 0.5 W, could be achieved.

Keywords

Breast Tumor, Cancer Treatment, Thermotherapy, Microstrip Antenna

1. Introduction

Breast cancer has occupied the highest rate worldwide among other cancers [1] [2], requiring earlier treatments. Compared to other treatments based on radiotherapy-method, chemotherapy-method, and hormone-method, hyperthermia (known as thermotherapy) has been considered an effective method for breast cancer treatment [3]. It acquires malignant tissues to increase their temperature level higher than 42˚C to improve the blood-flow level within the tumors where the oxygenation rate is naturally lower [4]. According to the tumor location inside the human body, hyperthermia treatments are distinguished into three different types, namely local, regional, and entire-body hyperthermia [5]. Local hyperthermia is applied to heat a smaller specified area on the skin layer, whereas regional hyperthermia is preferred for tumors located under the skin tissue. Likewise, whole-body hyperthermia is used for the entire body where tumors are located deeper inside the biological tissues. Commonly, thermotherapy could be achieved by means of numerous techniques such as thermal conduction, ionizing-ultrasound, and radio frequency (RF) [6]. The non-ionizing RF approach has reserved a considerable place compared to other ionizing ones, where the patch antennas are the core element essentially for breast tumor treatments. Several designs of antennas have been introduced in literature [7] [8] [9], however, there is a deficiency in studying multiple tumors. Furthermore, the enhancement of the return loss, and the simplicity in terms of the shapes, feed, and cost are still prerequisites for the practical use of antennas.

The current work proposes a single-slotted antenna functioning at 2.45 GHz for breast cancer treatment based on microwave hyperthermia, where the simulated result of the suggested antenna shows a decent return loss. The following stage was to estimate the specific absorption rate (SAR) inside the breast tissues at different values of input power, and the SAR presented a good result at the tumor center when a reasonable power was applied. The SAR level was well managed under the recommended IEEE level of 1.6 W/kg through the surrounding healthy tissues. For hyperthermia, a breast covered by nine-slotted rectangular antennas is designed and simulated using an EM-Thermal coupled solver in the CST suite. In that, the temperature profile as a function of treatment time was presented and a favored temperature for hyperthermia purposes was reachable through a reasonable time. Using three antennas simultaneously to treat multiple tumors is discussed, where the analysis here is to clarify the concept in the first instance, but, the eventual goal is to realize a phase antenna array to efficiently focus the RF radiation on a deeper tumor without harming healthy tissues.

The presented work is intended over different sections as Section 2 describes the schematic layout of a single-slotted rectangular antenna operating at 2.45 GHz using CST software, where the design specifications and the simulated antenna results are demonstrated as well. Section 3 presents the proposed breast phantom consisting of three layers by characterizing their dielectric features alongside the SAR level. Section 4 discusses the simulated results of the whole model in terms of the temperature distributions for hyperthermia treatment purposes. Section 5 summarizes the current work and gives associated future points.

2. Antenna Design Specifications and Results

Two different designs of a rectangular patch antenna resonating at 2.45 GHz are explored in the current section. Using CST software, schematics of these designs are shown in Figure 1 where the front side of the design-1, the back side of the two designs, and the front side of the design-2 are presented individually in Figures 1(a)-(c), respectively. As per design specifications, the height of an FR-4 substrate was planned at 1.6 mm with a permittivity of 4.3, whereas the physical dimensions were optimized for the two designs and illustrated in Table 1.

The potential results of the designs are evaluated using the reflection coefficient (S_{11}) parameter as demonstrated in Figure 2. Design-1 represents the typical configuration of a rectangular patch antenna, where the S_{11} shows a high reflection below −10 dB and a slightly shifted from the planned frequency of 2.45 GHz. Design-2 describes a modified version of design-1 by considering inset-fed and a rectangular slot at the center of the patch, resulting in an improved S_{11} better than −47 dB at 2.45 GHz. A comparison performance between the two designs is summarized in Table 2. From this, it is obvious that design-2 showed a reasonable performance preferred for breast cancer treatment purposes, as it will be investigated in the next sections.

3. Breast Phantom Structure

A simple breast, consisting of three tissues combining a tumor located at the breast center, is modeled as shown in Figure 3. These biological tissues in ascending order are the breast-fibro glandular layer, breast-fat layer, and breast-skin

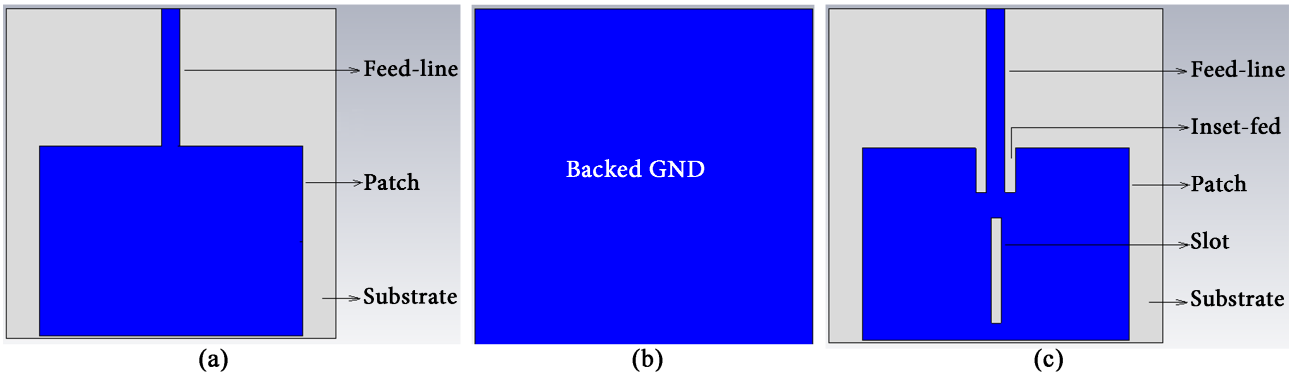


Figure 1. Configurations of the proposed antennas. (a) Front side of Design-1; (b) Back side; (c) Front side of Design-2.

Table 1. Optimized dimensions of the two antennas.

Parameter	Design-1		Design-2	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)
Backed GND	50	50	50	50
Substrate	50	50	50	50
Patch	28.73	40	28.73	40
Feed-line	20.87	2.80	20.87	2.80
Inset-fed	N/A	N/A	6.58	1.57
Slot	N/A	N/A	15.68	1.47

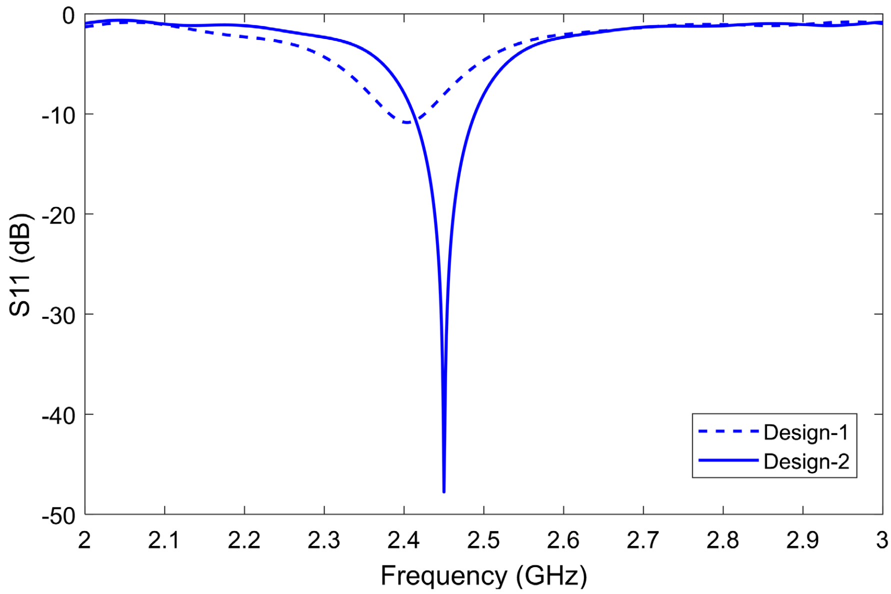


Figure 2. The S_{11} performance as a function of frequency.

Table 2. A comparison performance of the two proposed antennas.

Outcome	Design-1	Design-2
Reflection coefficient	−10.7 dB	−47.7 dB
Bandwidth	45 MHz	78 MHz
Resonant frequency	2.38 GHz	2.45 GHz
Simulated power	0.5 W	0.5 W
Accepted power	0.398 W	0.499 W
E-field	15.5 dBV/m	16.7 dBV/m

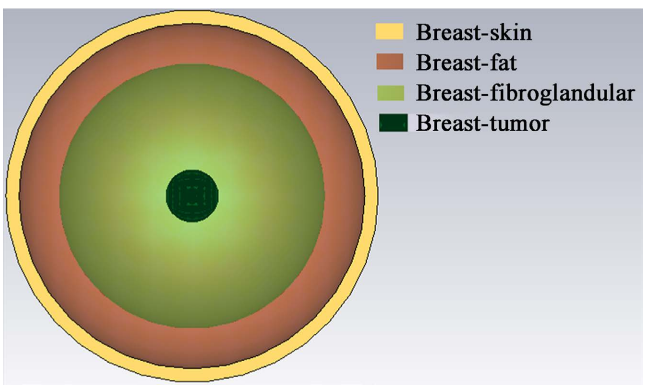


Figure 3. A breast model layers including a tumor.

layer. The three layers are described via their dielectric features, namely conductivity, mass density, and permittivity, where their standards at 2.45 GHz are presented in **Table 3**. Physically, the breast phantom is built, using CST studio, through two hemispheric shapes representing both breast-skin and breast-fat layers with radiuses of 70 mm and 65 mm whereas their thicknesses are 5 mm and 15 mm, respectively. The breast-glandular and the tumor are designed as spherical layers with diameters in respective of 100 mm and 20 mm.

Prior to the hyperthermia treatment phase, the absorbed power by the breast tissues should be restricted below a SAR level of 1.6 W/kg for 1 g mass as guided by IEEE [11]. To clarify, the intended antenna is placed at a distance of 10 mm from the breast phantom. As a result, the SAR at the tumor center is estimated by applying different values of input power as exhibited in Figure 4. It is clearly seen that there is a linear association between applied and absorbed powers (SAR) inside the breast model at which the highest value of the input power

Table 3. Dielectric characteristics of breast layers [10].

Tissue Type	Conductivity (Sm^{-1})	Mass Density (kgm^{-3})	Permittivity
Breast-tumor	4	1040	50
Breast-fibro glandular	0.45	1040	14
Breast-fat	0.4	900	9
Breast-skin	4	1100	36

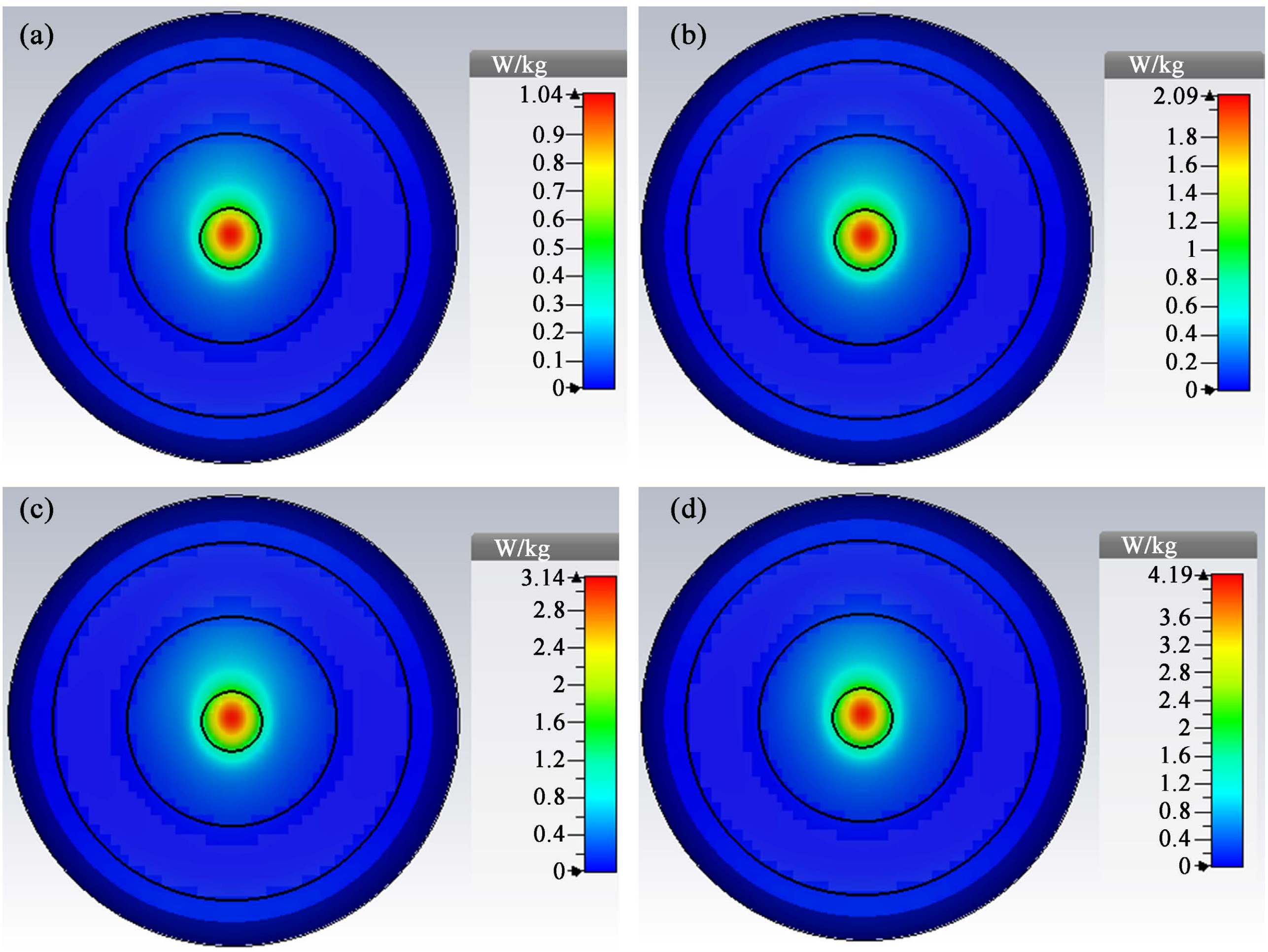


Figure 4. SAR as a function of applied powers. (a) Power of 0.5 W; (b) Power of 1 W; (c) Power of 1.5 W; (d) Power of 2 W.

should be restricted at 1.5 W, shown in Figure 4(c). In other words, this power level induces a higher SAR value of 3.14 W/kg at the tumor location while keeping the enclosed health tissues well below the IEEE limit of 1.6 W/kg. The higher SAR leads to a high-temperature profile, giving a reasonable drive to use the proposed antenna for hyperthermia cancer treatments. This will be explored further in the next section by considering a temperature distribution inside the breast phantom.

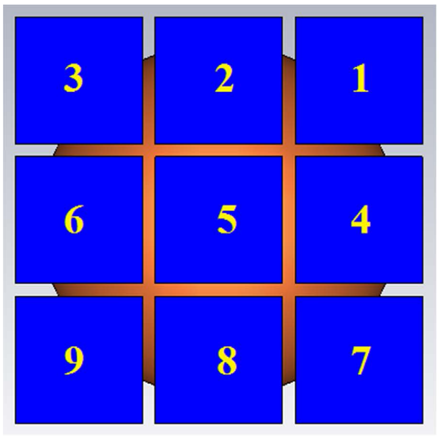
4. Hyperthermia Treatment Results

As a whole, the breast phantom receives and absorbs the emitted electromagnetic (EM) signals from the proposed antenna, leading to induced temperatures preferred for hyperthermia therapy. To follow this, the thermal properties of tissues are assigned as illustrated in Table 4 whereas the ambient temperature is allocated at 37˚C. Figure 5 describes the planned treatment model covered by nine antennas labeled in Figure 5(a), where the input power for every single element is 0.5 W. By considering a single tumor located at the breast center and only applying the associated antenna labeled 5, the potential performance was estimated via a coupled EM-Thermal simulation in a CST environment.

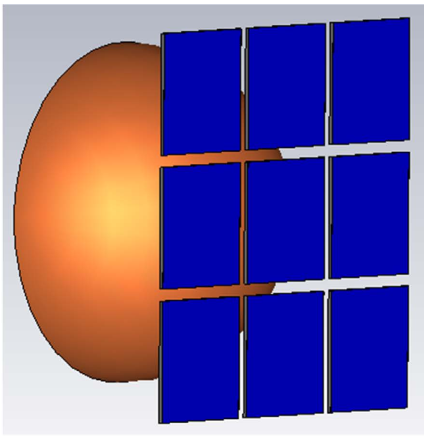
Figure 6 shows the temperature profile inside the phantom as a function of exposure time, where the maximum temperature taken into account is attained

Table 4. Thermal characteristics of breast layers [10].

Tissue Type	Metabolic rate [W/m³]	Blood flow [W/K/m³]	Heat capacity [kJ/K/kg]	Thermal conductivity [W/K/m]
Breast-tumor	N/A	N/A	4.186	0.6
Breast-fibroglandular	60,000	400,000	3.700	0.624
Breast-fat	60,000	400,000	3.600	0.624
Breast-skin	300	2000	2.500	0.201



(a)



(b)

Figure 5. A proposed arrangement of the treatment model. (a) 2D View; (b) 3D View.

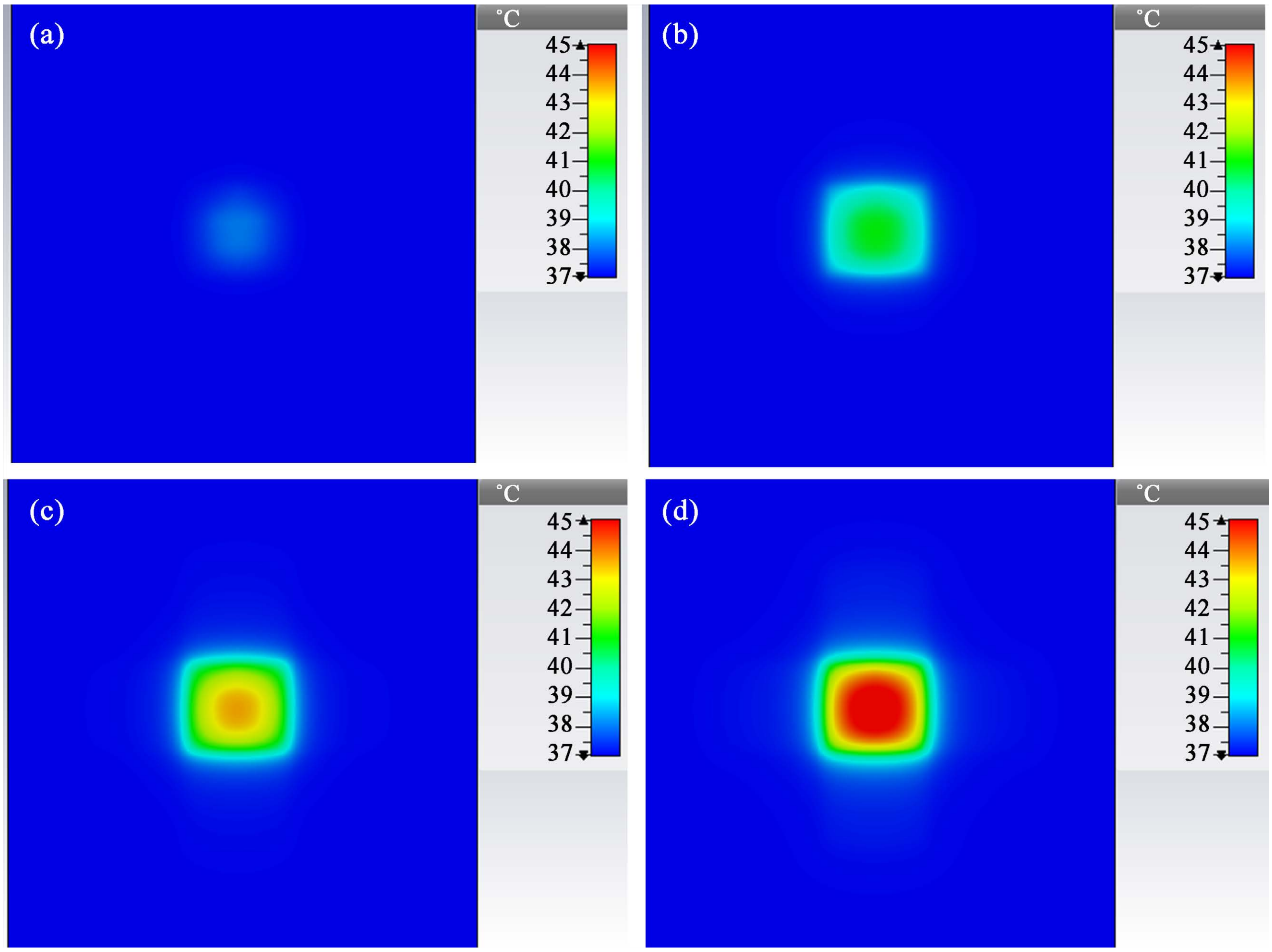


Figure 6. A maximum temperature inside the breast model based on antenna-5. (a) 38˚C @ 60 s; (b) 40.9˚C @ 300 s; (c) 43.6˚C @ 600 s; (d) 45.6˚C @ 900 s.

at 45˚C. As can be observed, the preferred temperature for hyperthermia treatments (42˚C up to 45˚C) is obtainable at 600 s (10 minutes) as exhibited in Figure 6(c). For the sake of multi-tumors, the tumor is relocated at the upper right of the breast where the antenna labeled 1 is a leading candidate. As a result, the performance is still consistent with the previous one as introduced in Figure 7. This provides the opportunity to treat three tumors using three antennas simultaneously with 0.5 W of input power, where the maximum SAR was found at 1.5 W as resulted in the previous section.

5. Conclusion

Hyperthermia treatment for breast cancerous tissues based on a slotted patch antenna was explored in this current work. The investigation was initiated by designing a single-slotted antenna, which showed an improved return loss of −47 dB with a bandwidth of 78 MHz at the intended frequency of 2.45 GHz. The following phase was to study the specific absorption rate (SAR) at which it attained a good result, below the specified IEEE level of 1.6 W/kg, at an input power of 1.5 W. This preferred SAR level was further exploited to study the

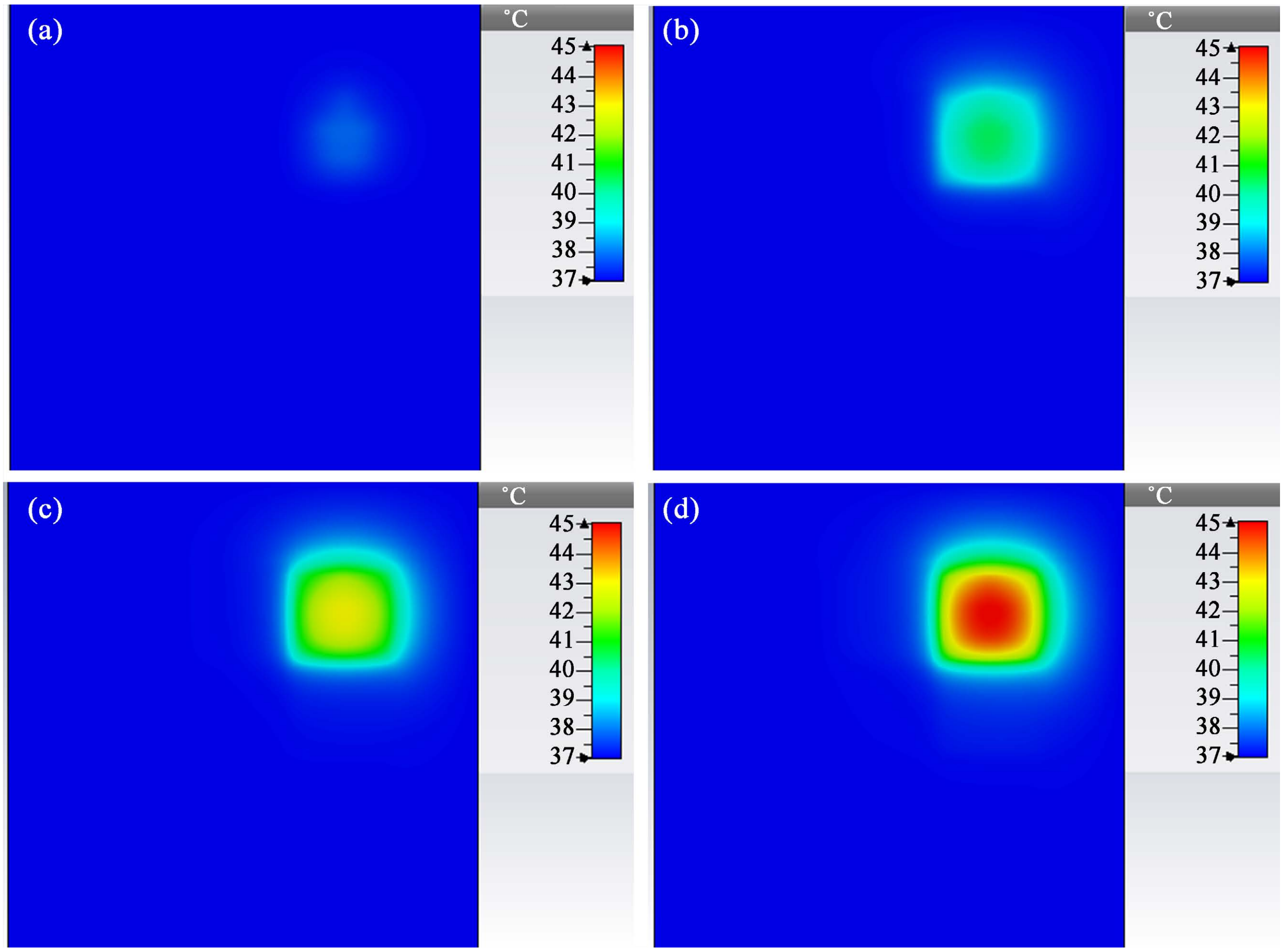


Figure 7. A temperature profile inside the breast model based on antenna-1. (a) 37.8˚C @ 60 s; (b) 40.4˚C @ 300 s; (c) 43˚C @ 600 s; (d) 45˚C @ 900 s.

temperature distributions inside the breast model, considering nine element antennas and two tumors located at different positions. As a consequence, the temperature profile as a function of exposure time was presented where a temperature of 43˚C, favored for hyperthermia purposes, resulted in 10 minutes. According to the resultant SAR value, the simulated results indicated the potential use of employing three element antennas, each with 0.5 W instantaneously, for multiple tumors' treatment. The current study was to prove the concept in the first instance, however, the beneficial aim is to recognize a phase-antenna array to focus and deliver the EM signal into a deeper tumor avoiding overheating healthy tissues. To confirm the current simulated outcomes, the next stage will consider the fabrication and measurement steps.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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