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Research Article

Design and Optimization of a Miniaturized Antenna for Targeted Hyperthermia in Tumor Therapy

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Abstract

Hyperthermia (HT) is a cancer treatment that involves applying heat to tumor tissues, often in combination with radiation or chemotherapy, to help inhibit tumor growth. Compact antennas will play a crucial role to facilitate localized heating by directing electromagnetic energy specifically to tumor regions. This article introduces a cost-effective, compact, and lightweight circular slot-shaped rectangular antenna (CSRA), a microstrip antenna designed for hyperthermia tumor treatment. It explores the use of hyperthermia as a treatment method, which, while effective, can cause overheating of surrounding healthy tissues, leading to the formation of hotspots. The antenna is modeled within a combined single-layer human tissue model and simulated using Ansys HFSS 2020R1 software. The compact (30 × 30 mm²) rectangular microstrip antenna operates at a resonant frequency of 2.4 GHz, offering a bandwidth of 40 kHz and a return loss of -20.8 dB. The Specific Absorption Rate (SAR) is calculated along the x-axis within the phantom at a 26.27 mm penetration depth, all of which comply with IEEE standards for safety and performance. Simulated results are validated through measurements and compared with recent literature. The findings, including the antenna's size and design, confirm that this slotted circular antenna is a promising candidate for microwave hyperthermia treatment of tumors.

Keywords

Circular Slot Shaped Rectangular Antenna, Specific Absorption Rate (SAR), Hyperthermia Application

1. Introduction

Hyperthermia is the process of elevating the body's temperature, either overall or in a specific area, above the normal range, typically between 40 and 44 ℃, for a set duration [1]. A key factor in raising the temperature within the body's tissues is the absorption of radiofrequency (RF) or microwave power, which is measured by the specific absorption rate (SAR) [2]. At these elevated temperatures, malignant cells are destroyed by damaging their proteins and altering their structure. Antennas play a crucial role in hyperthermia systems, as they generate the electromagnetic waves necessary for temperature increase. By manipulating excitation signals, it is possible to precisely target the tumor site while

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minimizing power deposition in healthy surrounding tissues [3]. The amplitudes and phases of these signals are controlled to enhance the fields in the targeted area while reducing them elsewhere. Several studies have explored RF and microwave applicators for non-invasive local and regional hyperthermia [4-6]. The heating frequency for hyperthermia application depends on the tumor's proximity to the skin. Superficial hyperthermia applicators (local hyperthermia) typically use a large single antenna [7] for tumors near the skin, while multi-antenna systems are used for deeper tumors (regional hyperthermia). Studies indicate that the 2.4 GHz industrial, scientific, and medical (ISM) radio bands are suitable for tumors in the head and neck region [8]. The Hyper Collar has been developed for targeted, tumor-conformal heating in this area, allowing better control over power distribution within the body [9]. The performance slot antennas can also be influenced by feed networks [10]. Antenna design for hyperthermia applicators is complex and differs from that in free space [11, 12]. To optimize the electromagnetic interaction between irradiation fields and human tissues, hyperthermia antennas are submerged in a cooling liquid bolus, such as purified water, which also cools the skin after it is briefly heated [13, 14]. Additionally, the size of the antenna is reduced relative to its operating frequency. The rapid progress of various biomedical and other applications has sparked the need for the miniaturization of the antenna [15, 16]. Nowadays, the highly spread wireless network sensing protocols as per IEEE Guidelines utilize in ISM band range 2.4 GHz. The circular-shaped slot antenna is expected to outperform patch, waveguide, and other antennas commonly used in hyperthermia applicators due to its compact size and superior performance [17-20]. When combined with magnetic resonance imaging (MRI), conductive hyperthermia offers significant advantages. Other devices, like patch antennas, can obstruct signal reception and transmission in an MRI scanner. This paper introduces a new and compact size antenna designed for the 2.4 GHz ISM band, based on a circular-shaped configuration. Details of the antenna design are described, and simulated and measured results which include return loss and other parameters like E-field, surface currents, and SAR measurements discussed. The first section of this manuscript gives a brief introduction of hyperthermia tumor therapy and role of compact structure. The second section discusses the proposed antenna design and their applications based on size in the ISM band range. In the next section, we discussed the characterization of the proposed structure having parameters like reflection coefficients; the final section discussed the fabrication, measurements and conclusion of applications.

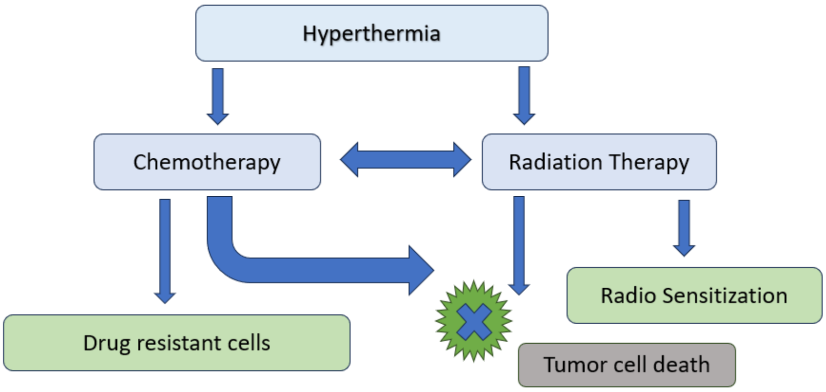

Figure 1. Hyperthermia enhances conventional cancer therapies, including chemotherapy and radiation, in eliminating tumor cells.

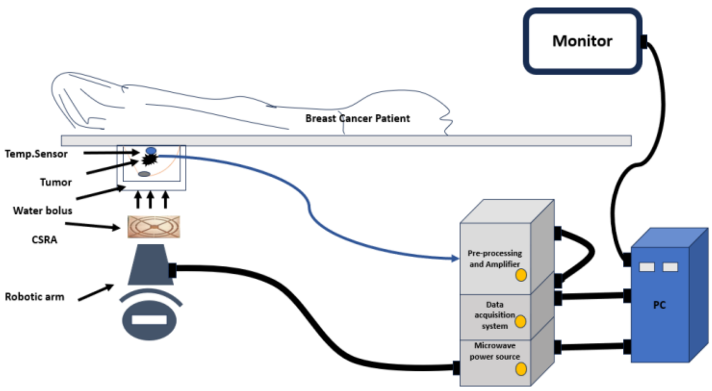

Figure 2. Hyperthermia tumor cells cancer detection setup.

2. Design and Analysis of Structure

The configuration of the designed antenna is shown in Figure 3. The substrate is made of FR4, which has of 30x30x1.6 mm^3, a dielectric constant of 4.4, and a loss tangent of 0.02. Our suggested antenna's radiating elements are circular slots. The antenna design started with a small circular slot in the centre of the patch with a diagonal slot cutting to the edges of the patch. A 50Ω coaxial feed at position (x=0, y=-3.5 mm) is connected. After that 4-circular slot arc was cut to improve the isolation as well as to achieve the desired frequency, and finally 4-concentric slot arc was cut and get the resonance at 2.4 GHz with good isolation.

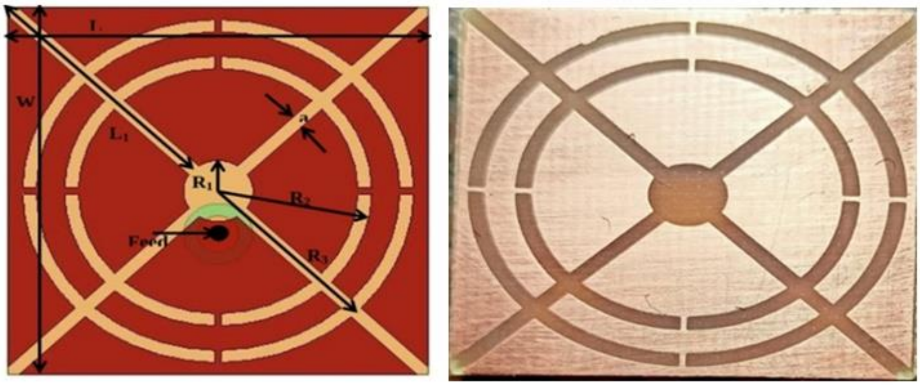

***Figure 3.** Fabricated and Simulated Proposed structure design top view.*

The ANSYS HFSS software was used to simulate this proposed Antenna. Radius R_1 of microstrip patch antenna [21]:

$$R_1 = \frac{F}{\sqrt{\left\{1+(2h/\pi\varepsilon_r F)\ln\left(\frac{\pi F}{2h}\right)+1.7726\right\}}} \quad (1)$$

Where,

$$F = 8.791\times 10^9 / f_r\sqrt{\varepsilon r} \quad (2)$$

The Finite Element Method (FEM) proves to be an effective instrument for analyzing the anticipated antenna functionality. The transmission of electromagnetic waves through coaxial feeds can be elucidated through the depiction of transverse electromagnetic fields (TEM). With a focus on time-harmonic fields, the progression of waves is delineated through Equations (3) to (5) [22].

$$E = e_r \frac{C}{r} e^{j(wt-kz)} \quad (3)$$

$$H = e_{r\varnothing} \frac{C}{R} e^{j(wt-kz)} \quad (4)$$

$$P_{avg} = e_z \frac{C^2}{Z} \ln\frac{r_{inner}}{r_{outer}} \quad (5)$$

Where,

$$k = 2\pi/\lambda \quad (6)$$

In the context of the coaxial cable, r, ∅, and z represent the cylindrical coordinates, with z denoting the propagation direction. Z stands for the wave impedance within the cable's dielectric. Pavg signifies the average power transmission. r_{inner} and r_{outer} respectively denote the radii of the inner and outer conductors. The antenna behaviour is governed by Maxwell's equations, which are illustrated in equations (7) - (10).

$$\Delta \times E = -j\omega \leftarrow \mu \rightarrow . H - Mimp \quad (7)$$

$$\Delta \times H = -j\omega \leftrightarrow \varepsilon . E - Jimp \quad (8)$$

$$\Delta.(\varepsilon . E) = -\frac{1}{j\omega}\nabla . J_{imp} \quad (9)$$

$$\Delta.(\mu . H) = -\frac{1}{j\omega}\nabla . M_{imp} \quad (10)$$

Here, M_{imp} represents the magnetic current density, and J_{imp} denotes the current source that excites the antenna. To accurately assess the antenna's performance, we need information regarding the length and width of the slot antenna. The length of the slot is given as

$$L_{slot} = \frac{\lambda_g}{4} = \frac{c}{4f\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (11)$$

The width of the slot is given as [23]

$$W_{slot} = \frac{\lambda}{60} \tag{12}$$

Figure 1 illustrates the evaluation process of the proposed antenna design. In order to minimize its size, slots are incorporated into the patch. Genetic algorithm optimization techniques are then employed on a circular-slot antenna to identify the optimal slot configuration for enhancing the surface current (J_s), thereby improving the reflection coefficient within the 2.42 GHz ISM band.

Table 1. Parameter of Design structure Antenna.

Parameter	Value (mm)
L	30
W	30
L_1	18.66
R_1	2.5
R_2	11
R_3	14
a	0.5

3. Results

This section provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn. Through rigorous simulations and empirical evaluations, the paper delves into the intricate interplay between the slot geometry, material properties, and the surrounding biological medium. Figure 4 shows the simulated and measured reflection coefficient results which are -20.8 dB and -23.8 dB respectively. And having a bandwidth of 40 kHz.

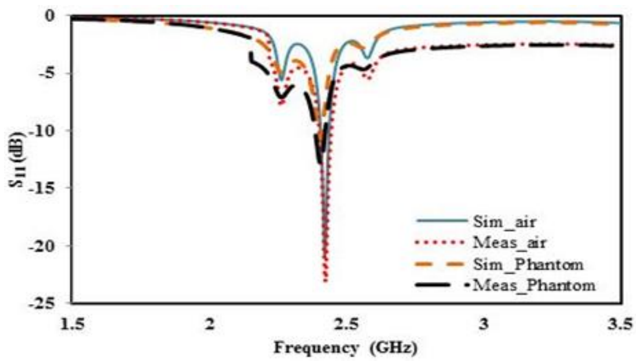

Figure 4. Simulated and measured reflection coefficient result Proposed Antenna.

This paper presents an in-depth analysis of the surface current behavior and electric field distribution in a slot antenna tailored for biomedical healthcare technologies. One crucial aspect of their performance is the interaction between surface currents and electric fields.

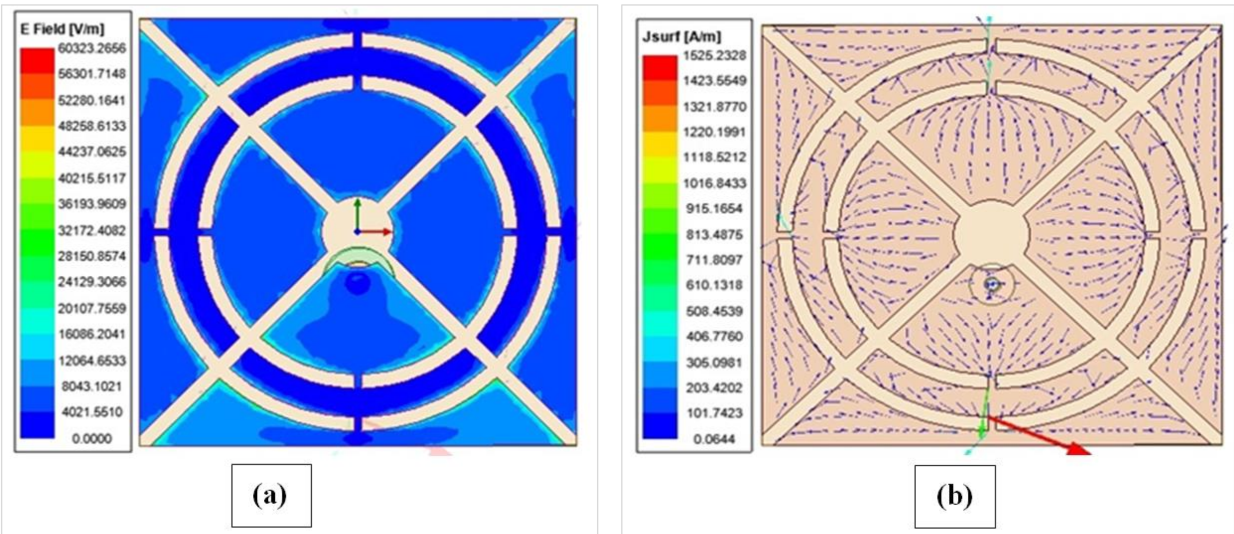

Figure 5. (a) Surface current plot (b) Electric Field Plot.

In this context, the surface current distribution along the slot edges plays a pivotal role in shaping the radiated electromagnetic field. Moreover, the electric field distribution surrounding the slot governs the antenna's ability to efficiently couple with biological tissues and transmit and receive signals. The evaluation of the Specific Absorption Rate (SAR) is critical in assessing the potential health hazards of electromagnetic radiation emitted by slot antennas, particularly in biomedical applications. In this section, we present the comprehensive SAR analysis conducted for slot antenna design in biological tissue commonly encountered in biomedical scenarios. To support this concept, the IEEE specifies the use of tissue-simulating liquid (TSL), also referred to as tissue-equivalent liquid (TEL), as a human-equivalent material for mimicking biological tissues. Measurements are conducted at varying or constant power levels and exposure durations to assess tissue damage based on electromagnetic energy absorption in the TSL. It is a cubic box of human muscle tissue, with ε_r = 52.7, σ = 1.74 S/m at 2.45 GHz. The SAR distribution was computed using a high-frequency structural simulator simulation technique. The antenna was excited with a typical input power level (12.3mW) corresponding to the intended application scenario. A heterogeneous voxel-based human body model (90mm×90mm×26.27mm) with an open-access database, incorporating realistic tissue properties, was used to simulate SAR distribution. Figure 6 depicts the simulated SAR value as 130.08W/kg. The SAR results help to detection of hyperthermia tumor therapy.

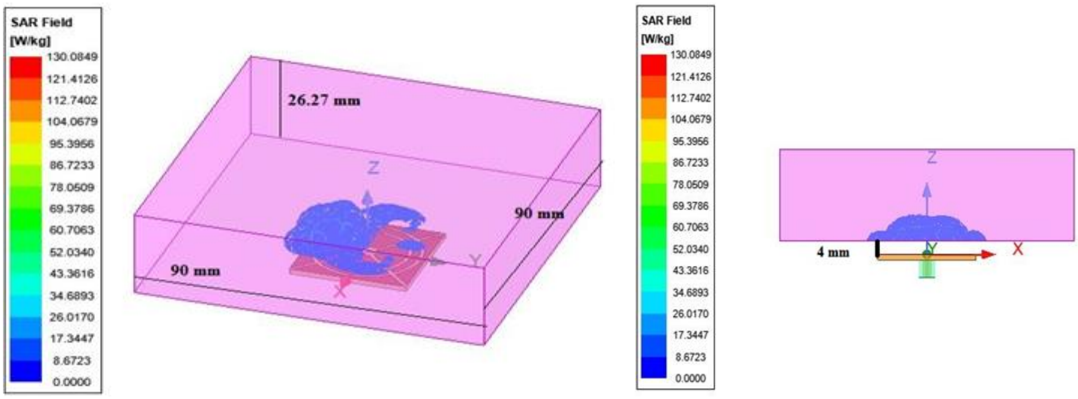

Figure 6. Surface Contour Plot (a) 3D-view of SAR contour plot (b) Side-view of SAR contour plot.

This proposed structure having good polarization, for biomedical applications, maintaining a consistent polarization is essential for minimizing signal distortion and maximizing communication reliability.

4. Measurement Setup

The fabrication process involves advanced techniques of photolithography fabrication to achieve precise slot dimensions and geometries. The slot antenna's resonance characteristics are optimized to ensure efficient energy transfer within the 2.4 GHz ISM frequency band, and the volume of this slot antenna is relatively less but it should not suitable for SAR measurement applications because it has more reflection loss S_{11} as compared to our proposed work, catering to specific biomedical sensing requirements. To validate the antenna's performance, rigorous measurements are conducted using equipment (R&S ZNA series) in controlled environments, and biological conditions. The reflection coefficient S_{11} and fabricated proposed antenna are shown in Figure 7(a). The specific absorption rate setup in Tissue equivalent liquid is shown below in Figure 7(b).

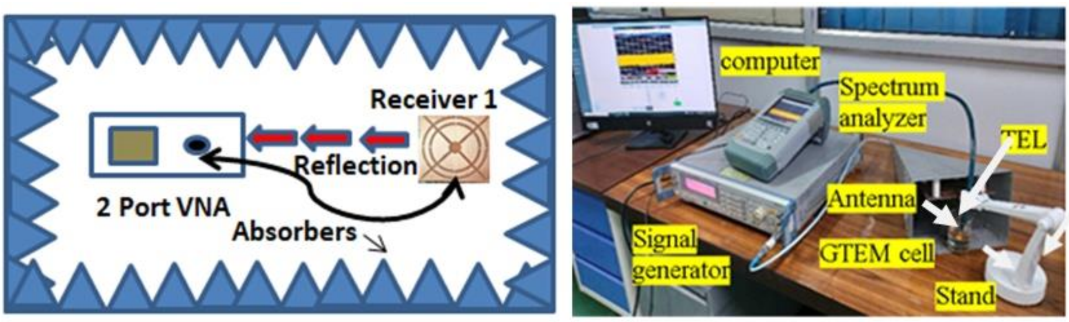

Figure 7. Measurement setup (a). Reflection coefficient S_{11} (b) E- Field Measurement in TEL.

Table 2. Comparison of Proposed Antenna to Others.

Ref	Freq. App. (GHz)	Volume (mm^3)	S_{11} (dB)	PD (mm)
[13]. (2017)	2.1 ISM	140x75x0.8	<-10	NR
[14]. (2018)	2.4 ISM	44x44.5x1.55	-52.8	NR
[24]. (2022)	2.5 ISM	68x73x1.6	≤-10	NR
[25]. (2022)	2.4 ISM	32x32x3.27	≤-10	NR
[26]. (2023)	2.4 ISM	50x50x1.6	-47	15
[27]. (2024)	2.4 ISM	35x26x1.6	-40	NR
This Work	2.4 ISM	30×30×1.6	-20.8	26.27

*NR-Not Reported

5. Conclusion

The presented compact antenna is designed to reflect electromagnetic signals at 2.4 GHz, making it suitable for local hyperthermia tumor detection. To fine-tune the frequency bands, two circular-shaped slots are added to the main cross-slot, all etched on the ground plane. This design approach ensures efficient antenna reconfiguration, offering a cost-effective solution. The key advantages of the antenna include its compact size, innovative design, and ability to cover the ISM frequency band, making it an ideal candidate for hyperthermia tumor therapy and other biomedical applications. This methodology has great potential for a wide range of applications in the biomedical field.

Abbreviations

HT	Hyperthermia
CSRA	circular Slot-shaped Rectangular Antenna
SAR	Specific Absorption Rate
MRI	Magnetic Resonance Imaging
FEM	Finite Element Method
TEM	Transverse Electromagnetics
RF	Radiofrequency
ISM	Industrial, Scientific, and Medical

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

Conflicts of Interest

The authors declare no conflicts of interest.

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