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An Investigation on the Effectiveness of a Novel Bowtie Antenna for Biomedical Applications

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ABSTRACT- Microwave breast imaging uses longer-wavelength, low-power waves to deliver comprehensive breast tissue information for safer and more accurate breast cancer diagnosis. This is an alternative to other more traditional approaches such as ultrasound, Positron Emission Tomography (PET) and X-ray mammography. This paper aims at discussing performance summary of bowtie antenna with slits loaded to detect breast cancer. The antenna that can be found in the present paper has a frequency band of operation of 4 GHz to 6 GHz and consists of a triangular patch fed by a rectangular feed line. The FR4 substrate with dielectric constant is 4.3 is exploited to make phantom models with and without a tumor and antenna models with or without slits. These designs are simulated and their effectiveness evaluated using CST software. According to the simulation results, the suggested bowtie antenna design is suitable for fabrication because it produces SAR values of 0.826 and 0.792 for phantoms with and without tumors, respectively, along with directivity values of 7.18 and 7.24. Slits in the antenna structure have been shown to be useful in modifying the resonant frequency, allowing the antenna to satisfy the specifications needed for medical imaging applications.

Keywords: Breast Cancer Detection, Microwave Breast Imaging, Phantom, Electric Field Distribution, Magnetic Field Distribution, Specific absorption rate (SAR), Non-invasive.

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1. INTRODUCTION

Breast cancer affects millions of women worldwide and remains a significant global health issue, as defined by the World Health Organization (WHO). Better survival rates, as well as patient outcomes, are mostly related to early detection, which is why the process of screening tests and diagnostic tools development becomes more crucial. Despite their effectiveness, traditional screening techniques like mammography have drawbacks such as ionizing radiation exposure and decreased sensitivity in dense breast tissue. This has prompted studies into non-invasive, alternate detection methods. In this regard, a potential approach to breast cancer diagnosis is electromagnetic based. This method's basic tenet is that breast cancerous tissue has distinct dielectric characteristics from healthy tissue. An analysis of how electromagnetic waves interact with breast tissue can be used to leverage this distinction. By failing to distinguish cell/normal malignancy tissue, 4%–34% of breast tumors are overlooked. "The use of microwave imaging (MI) to detect breast cancer appears to be promising by Nahalingam & Sharma [1]. The advantages of microstrip antenna MI include comfort, affordability, and nonionizing safety. The dielectric difference between unhealthy and healthy tumor tissues is the foundation of MI techniques. Alsharif et al. [2] demonstrated Tissue conductivity and dielectric properties are used in different approximation maps to pathologically differentiate between healthy and diseased tissue. In order to diagnose breast cancer, electromagnetic waves are sent through the breast by the transmitting antenna, and the scattered waves are picked up by the receiving antenna as shown in Mahmud et al. [3]. Radar-based MI and microwave tomography have been investigated for the detection of cancer by Zhang et al., Grzegorczyk et al. & Guardiola et al. [4-6]". In earlier designs, the majority of UWB antennas had low pick-up and omnidirectional radiation. Receiving wires can be circular, Vivaldi, Bowtie, or smaller strip antennas, as reported by Lotfi Neyestanak, Choudhary et al., Lee and Chakrabarty, Adnan et al. & Liu et al. [7–11]. The wearability of body-driven antennas is frequently assessed. A wearable antenna is a component of communication apparel that offers safety, mobility, and tracking. Wearable antenna equipment that is lightweight, inexpensive, nearly repair-free, and requires no installation is required for all new applications by Ojaroudi and Ojaroudi, Elbasheed et al. & Karli and Ammor [12–14]. The suggested solution uses MI and wearability to detect breast cancer early by integrating into garments and wearing on the body. Ultra-wide bands can enhance wireless range beyond low frequencies. Patch antennas are adaptable in input and output characteristics and may be utilized from 1-100GHz.

1.1. Motivation

There are several reasons for the motivation of the present work, due to the shortcomings of conventional ways, which include: X-ray mammography, PET and ultrasound, etc. These methods can miss a large number of cases because of differences in tissue which emphasizes the need for more accurate and safer approaches. The objective of the paper is to close this important gap by proposing a new microwave imaging method. Even though it does not mention a formal literature survey, this text positions its contribution in contrast with existing techniques, what imply the review of current practices to build up for their shortcomings that this work aims to fill in.

1.2. Key contributions and novelty

The main contributions of this paper come from proposing a slits-loaded bowtie for microwave imaging of breast as well as providing the multilayered structure for wideband illumination and curvature tuning. The core novelties include:

• *Original Antenna Composition:* A triangle-shaped radiating patch fed by a rectangular feed line with the addition of cut slits on the radiating patch to be suitable for more operations. The resonance frequency of the proposed antenna is 5 GHz.

• *Peak Performance*: With good performance, the antenna yields outstanding performance parameters such as return loss of -43.379 dB and VSWR of 1.013, promising an excellent matching impedance ratio for optimal network efficiency in communication systems.

• *Safety and Efficacy*: The study demonstrates that the SAR values of the antenna (0.792 W/kg without tumor and 0.826 W/kg with a tumor) is far below the FCC's SAR limit and conform to safety standards for human-centered medical MR procedures.

• *Tumor Detection*: It can be summarized as that the analysis highest distinction of the work is achieving in a physical point distant from and recommendable for human tissue where detect it exists a tumor inversion and change in important parameters. It is seen that there appears to be a distortion in electric (E-field) and magnetic (H-field) patterns which shows a surface current flow also distortion. It measures an increase in SAR caused by the tumor, as a direct consequence of its electrical properties difference.

• *Medical Design*: The study shows that, by adding the slits on to antenna structure is a good method of tuning the resonant frequency of an antenna and this is very important requirement for medical imaging. With approximately 7dBi stable directivity, the antenna is also adequate for direction-focused imaging. The work reports on a promise of a flexible substrate and potential application to wearable in the future.

The remainder of this paper is organized as follows, where in *section 2*, the consideration for antenna design presented and in *section 3*, provides Phantom model's design using the recommended antenna. *Section 4* has the results of the simulation and the problem of cancer detection discussed and the conclusion is argued in *section 5*.

2. DESIGN OF BOWTIE ANTENNA

2.1. Antenna Structure

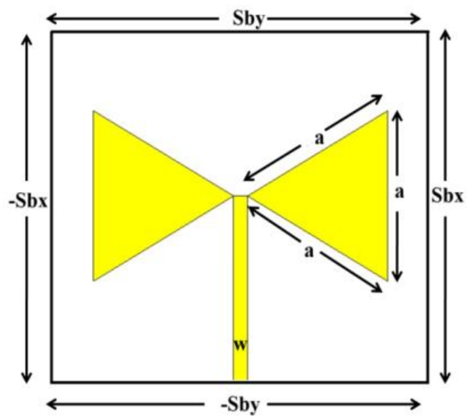

Figure 1. Proposed Bowtie microstrip patch antenna

When bowtie antennas encounter a discontinuity, like a wider patch, microstrip antennas radiate along the patch width, as shown in *figure 1*. Continuous patches do not radiate. To improve antenna performance, design parameters like *L, h, t,* and ε_r are set within particular ranges, as shown in *table 1* and the dimensions of the proposed bowtie microstrip patch antenna is shown in *table 2.*

Table 1. Range of different parameters

Parameter	Range
L	$0.3333\ \lambda_0 < L << \lambda_0$
h	$0.003\ \lambda_0 \le h \le 0.05\ \lambda_0$
ε_r	$2.2 \le \varepsilon_r \le 12$
t	$t << \lambda_0$

Where, λ_0 is the free space wavelength.

Table 2. Dimensions of proposed Bowtie microstrip patch antenna

Design Parameter	Dimension in (mm)
Substrate length	76
Substrate width	76
Thickness of patch	0.035
Ground length	76
Ground width	76
Substrate height	1.6
Each side of triangle	19.2897
Transmission line width	3.156

2.1. Design equations

The microstrip antenna's dimensions are determined by its resonance frequency. Consequently, the matching resonance frequency is established by Bhavani [18].

$$f_r = \frac{ck_{mn}}{2\pi\sqrt{\varepsilon_r}} \quad (1)$$

$$f_r = \frac{2c\sqrt{m^2+mn+n^2}}{3a\sqrt{\varepsilon_r}} \quad (2)$$

Where, the wave number can be ascertained by

$$k_{mn} = \frac{4\pi\sqrt{m^2+mn+n^2}}{3a} \quad (3)$$

Consequently, the lowest order resonance frequency is obtained from the equation above.

$$f_r = \frac{2c}{3a\sqrt{\varepsilon_r}} \quad (4)$$

Where f_r is the resonant frequency. Curve fitting is used to derive the equation for a_{eff}, which brings the TM10 mode resonant frequency measurements into line with theoretical predictions.

The dominant mode of resonance frequency is:

$$f_{10} = \frac{2c}{2fr\sqrt{\varepsilon_r}} \quad (5)$$

Side length:

$$a = \frac{2c}{2fr\sqrt{\varepsilon_r}} \quad (6)$$

Effective value of side length:

$$a_{eff} = a + \frac{h}{\sqrt{\varepsilon_r}} \quad (7)$$

Effective dielectric constant:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{4\sqrt{1+12\frac{h}{a}}} \quad (8)$$

2.2. Antenna Design and Geometry

The dimensions of this antenna are calculated by CST Microwave studio. *Figures 2(a)–(d)* display the progressive configuration of the antenna structure, as simulated in this section.

2.2.1. Antenna without slits

Slit-loaded modified structure is used which has two triangular shapes designed on either side of the radiating section and its geometry has been compared with a conventional microstrip patch antenna having a transmission line feeding. To assess the gains made possible by the geometric adjustments, the performance of the two designs was examined and contrasted. This comparison aids in comprehending how the slit-loaded structure affects the overall performance of the antenna.

2.2.2 Antenna with slits

The antenna's resonance frequency changed as a result of the initial design change, which involved cutting off slits nearby the edge on triangle patch. The antenna structure's change in resonant frequency will depend on the degree and slope of edges demonstrated by Niranjan et al., Karli et al. & Inum et al. [15-17]. *Figure 1(b)* illustrates the construction of an antenna with slits on edges.

2.2.3. Phantom in Bowtie Antenna without tumor

Finalize the antenna design and place it 58 mm from the breast phantom. To test the antenna's performance, CST software simulates scenarios with and without a tumor.

2.2.4. Phantom in Bowtie Antenna with tumor

Two scenarios are exploited to test the developed antenna: one with the insertion of a tumor in the breast phantom model and the other without it. The effect of the tumor on the antenna characteristics is investigated by comparing the respective structures simulated with CST. One advantage of this comparison is the ease at which one can understand what happens when a tumor appears in front of the antenna and its real losses are air-comparison since we can better visualize how the presence of such a tumor affects the proposed sensor's electromagnetic behavior and sensing capabilities.

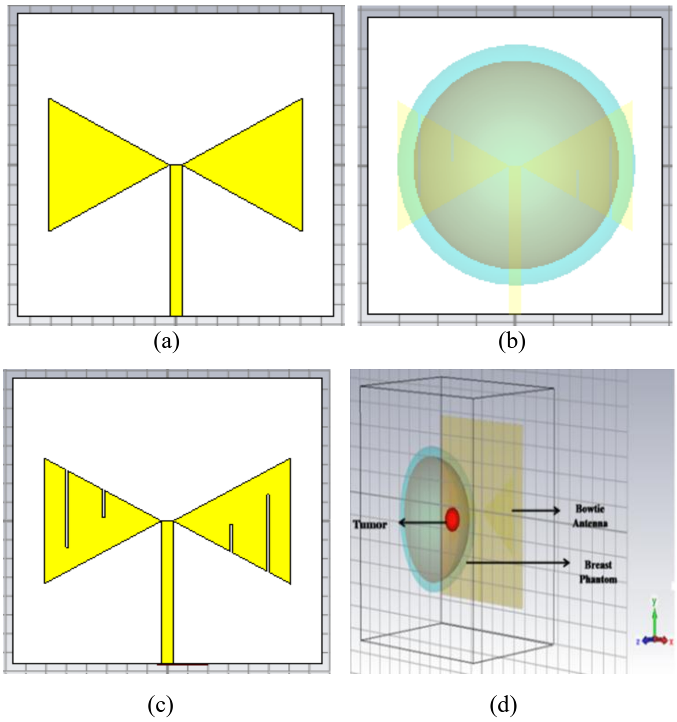

Figure 2. (a) Bowtie antenna without slits; (b) Bowtie antenna with slits; (c) Phantom in Bowtie antenna without tumor; (d) Phantom in Bowtie antenna without tumor

3. PHANTOM WITH PROPOSED BOWTIE ANTENNA

The process of creating a phantom model involves the following steps:

1. Skin parameters are used to construct the skin.
2. Material with fat properties is used to design fat.
3. Tumor parameters are used to design the tumor by Rakib et al., Hamd et al. & Elsaadi et al. [19-21].

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In this study, the development of the breast phantom model considers several critical factors, including the material properties of skin, fat, and glandular tissue. The specific parameters required to construct the breast phantom are detailed in *table 3.*

Table 3. Dimension for designing phantom

Parameter	Radius	Thickness
Brest Skin	32mm	4mm
Brest fat	28mm	21mm
Breast glandular tissue	23mm	2mm

The dimension parameters of the breast phantom are skin layer with radius of 32 mm and thickness of 4mm, fat layer with radius of 28 mm and thickness of 5mm, glandular tissue with radius of 21 mm. In the model, a 5 mm radius malignant tumor in a spherical form is added to be located at various locations within the breast phantom as shown in *figure 3*. Simulation of tumor detection under various conditions is performed with this structure.

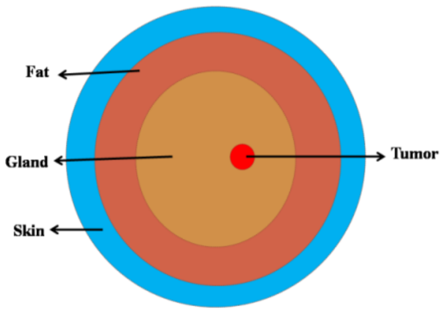


Figure 3. Different layers of breast tissue

The phantom should be made to resemble the normal human breast, which might differ in size and form from person to person. To replicate compression during mammography, the phantom might also need to have a realistic curvature and contour. Based on these factors, a bowtie-shaped antenna is employed in this study to cover the breast phantom's region and identify tumors. By contrasting the phantom's imaging properties and tumor detection capabilities with those of actual breast tissue and tumors under known circumstances, it should be verified. This might entail assessing the phantom model's correctness and dependability using statistical analysis or quantitative measurements. "The dielectric properties of breast tissues, including skin, fat, and glandular tissue, used in the design of the breast phantom model are provided in *table 4*".

Table 4. Breast tissue dielectric properties

Tissue	Relative Permittivity, ε_r	Conductivity, σ (S/m)
Skin	33-46	0.15-3.8
fat	11-18	0.1-0.2
Glandular tissue	28-40	0.1-3.0
Tumor	48-66	0.15-5.0

4. SIMULATION RESULTS AND DISCUSSION

The proposed antenna structure is analyzed using computer simulation technology (CST) microwave studio, which is displayed in *figure 4*. A systematic performance analysis is carried out, covering the cases with and without a tumor inside the breast. The performance of the antenna in breast cancer detection is analyzed by comparing return loss, VSWR, E-Filed, H-Field estimation and SAR as shown in Lee et al., Afyf et al. & Chaurasia et al. [22–24]. A significant analytical requirement for any antenna to radiate effectively is to have a predicted return loss value of less than -10dB and VSWR≤ 2.

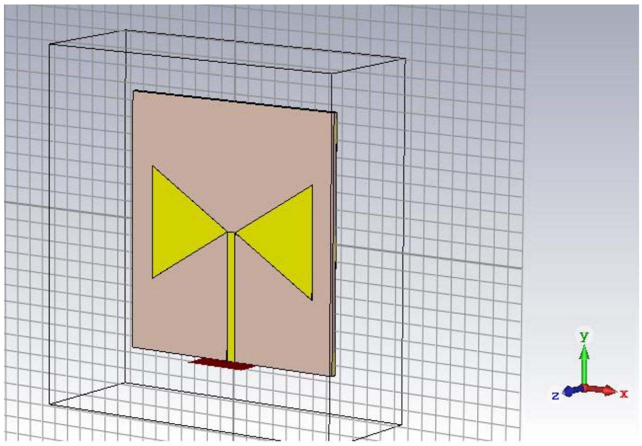


Figure 4. Proposed Bowtie antenna structure

Return loss: Return Loss v/s Frequency plot of the proposed Slitless Bowtie antenna is plotted in *figure 5*. The return loss of the proposed antenna is -39.403 dB, at a resonant frequency of 5.018 GHz, which verifies that there is low signal reflection and well impedance matching at this frequency.

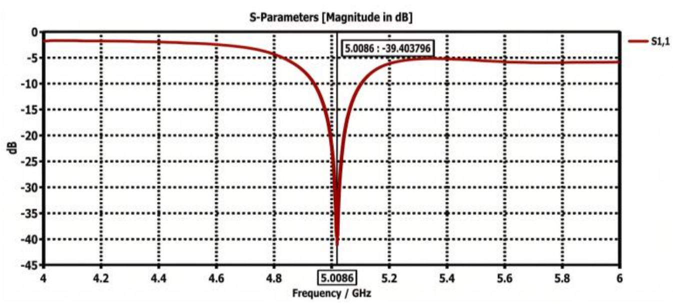


Figure 5. Return loss v/s frequency curve of the proposed Bowtie antenna without slits

VSWR: The VSWR v/s frequency plot of the proposed Bowtie antenna without slits is illustrated in *figure 6*. At the resonant frequency of 5.018 GHz, the VSWR is 1.058, indicating a good impedance matching and an efficient power transmission at this frequency.

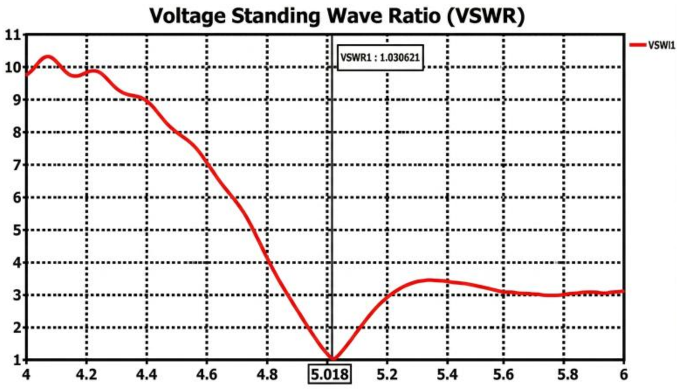


Figure 6. VSWR v/s frequency curve of the proposed Bowtie antenna without slits

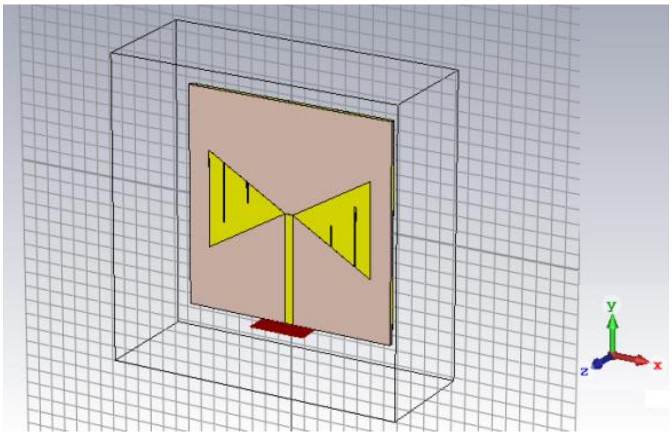


Figure 7. Proposed Bowtie antenna structure with slits

Return loss: *Figure 7* proposed Bowtie Antenna structure with slits. The return loss v/s frequency pattern of the proposed Bowtie antenna with slits is shown in *figure 8*. And the patch antenna with slot has better impedance match and signal transmission performance compared to that without slots, exhibiting a return loss of -43.379 dB at 5.02 GHz resonant frequency.

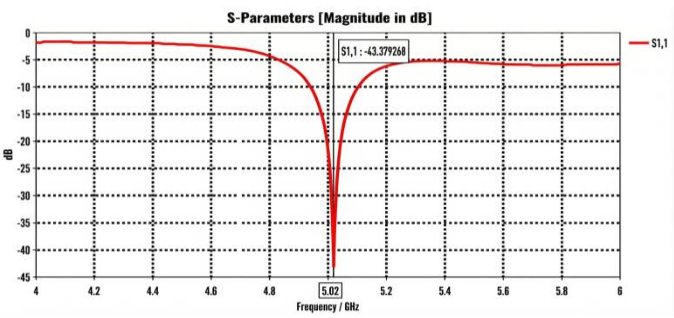


Figure 8. Return loss v/s frequency curve of the proposed Bowtie antenna with slits

VSWR: The proposed Bowtie antenna with slits' VSWR v/s frequency curve is displayed in *figure 9*. The antenna's virtually perfect impedance matching and efficient power transmission, as seen by its VSWR of 1.013 at the resonant frequency of 5.02 GHz, further highlights the enhanced performance of the slit-loaded design.

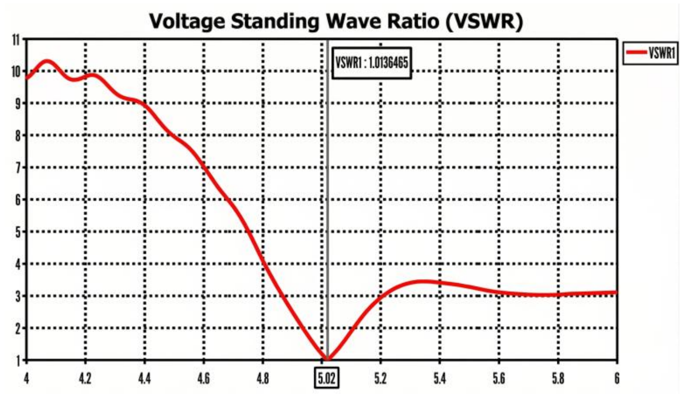
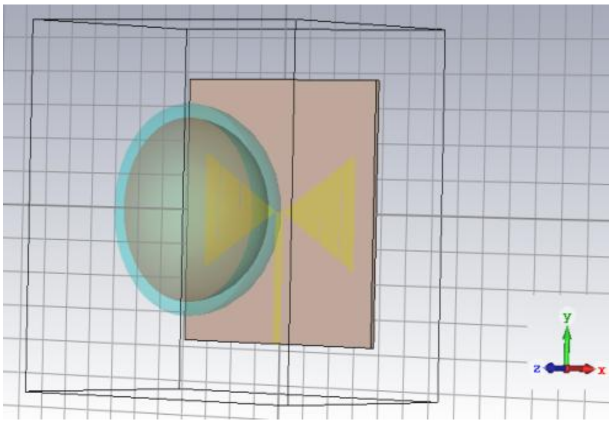
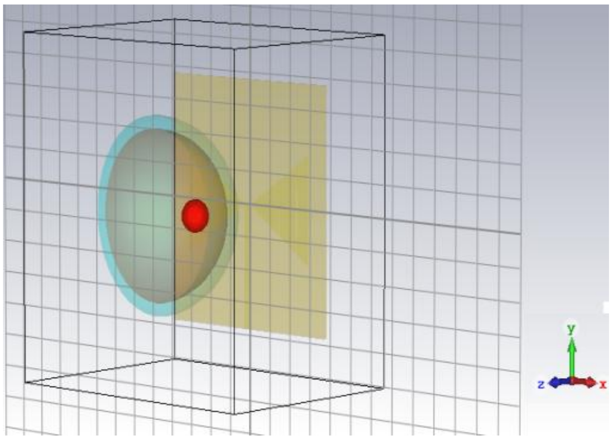


Figure 9. VSWR v/s frequency curve of the proposed Bowtie antenna with slits.

Analysis is performed on the breast phantom model using the Bowtie antenna for two scenarios of without and with a tumor, as shown in *figure 10(a)* and its counterpart in *figure 10(b)*, respectively. This comparison provides insight to the perturbation of the antenna's performance and its detection characteristics due to tumor.



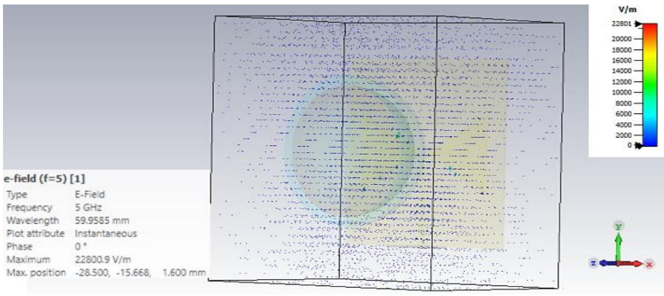
(a)



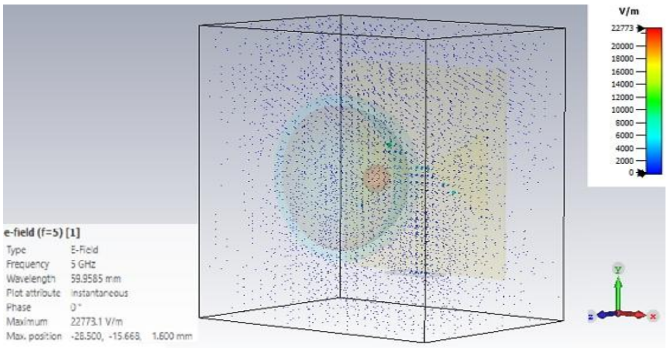
(b)

Figure 10. (a) Phantom in Bowtie Antenna without tumor; (b) Phantom in Bowtie Antenna with tumor

Electric field: The presence of a tumor disrupts the electric field, leading to variations in its intensity. Due to the tumor's distinct electrical properties, the electric field may either concentrate around or deflect away from the tumor. As a result, the electric field distribution in a phantom with a tumor significantly differs from that in a tumor-free phantom, as demonstrated in *figure 11(a) and 11(b)*.



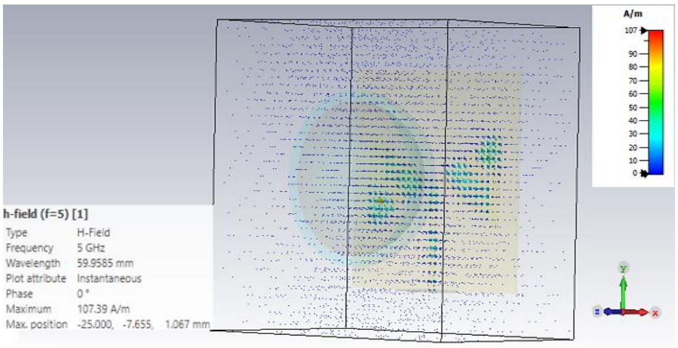
(a)



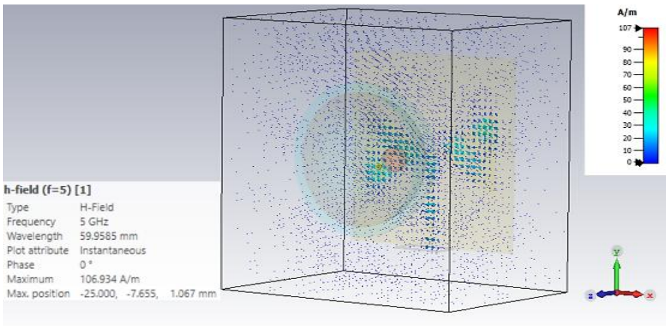
(b)

Figure 11. (a) Electric field of phantom in bowtie antenna without tumor (b) Electric field of phantom in bowtie antenna with tumor

Magnetic field: In MRI uses, the equipment creates a powerful and consistent magnetic field. A tumor or growth changes the way the protons in the tissue respond to this magnetic field. The tumor therefore causes a distinct distortion in the magnetic field and this may be utilized in the location and characterization of the tumor. The magnetic field distribution of the phantom model of a breast with and without a tumor is examined in both situations as depicted in *figures 12(a)* and *figure 12(b)*, respectively. These findings reveal the effects of the tumor on magnetic field, which offers information on how it can be detected and characterized.



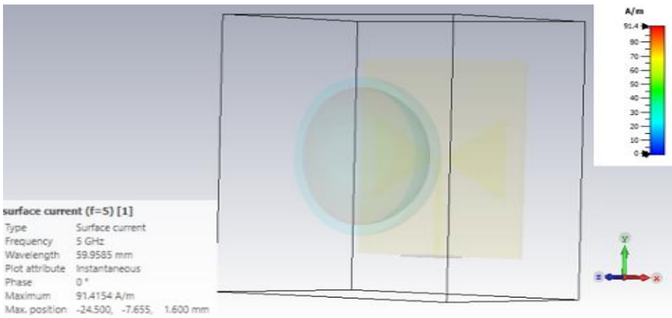
(a)



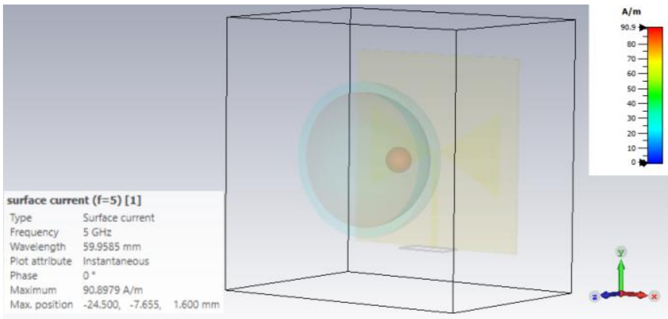
(b)

Figure 12. (a) Magnetic field of phantom in bowtie antenna without tumor (b) Magnetic field of phantom in bowtie antenna with tumor

Surface current: Tumors often exhibit higher conductivity compared to healthy tissue. The relationship between conductivity and surface current is pivotal in antenna design and performance. High-conductivity materials, combined with low-conductivity dielectric substrates, facilitate efficient surface current flow, which is essential for minimizing losses, achieving good impedance matching, and ensuring effective radiation. The surface current distribution of a phantom breast model with and without the tumor is shown in *figure 13(a)* and *figure 13(b)*.



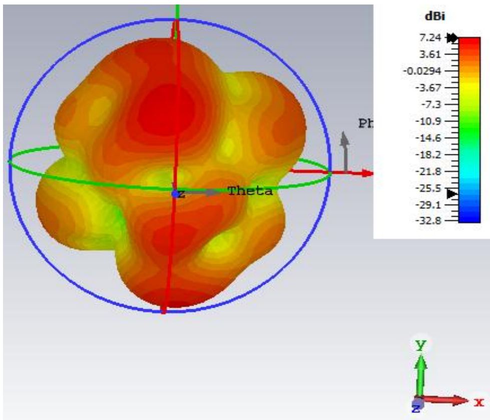
(a)



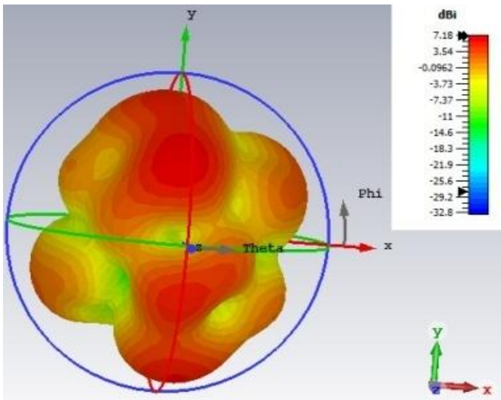
(b)

Figure 13. (a) Surface current of phantom in bowtie antenna without tumor (b) Surface current of phantom in bowtie antenna with tumor

Directivity: Directivity of fields passing through a phantom is changed by the presence of a tumor. Technology is also applied in therapies to increase the direction of the energy to the tumor. *Figure 14(a)* and *figure 14(b)* display the far-field directivity of the proposed phantom using a bowtie antenna, which are 7.24 dBi at 5 GHz without a tumor and 7.18 dBi at 5 GHz with a tumor.



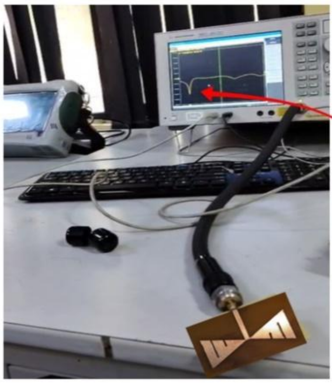
(a)



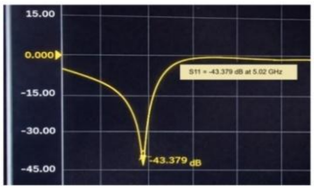
(b)

Figure 14. (a) Farfield of phantom in bowtie antenna without tumor (b) Farfield of phantom in bowtie antenna with tumor

Experimental Result: The proposed bowtie antenna with slits has been fabricated by using P.C.B. prototype machine. Experimental testing and verification done by using E5071C Network Analyzer in which the S11 measured is -43.379 dB at 5.02 GHz as shown in *figure 15(a) and 15(b)*.



(a)



(b)

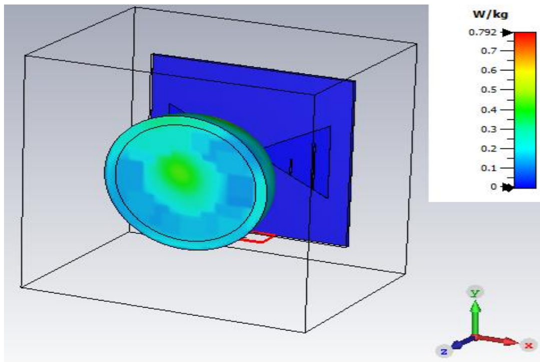
Figure 15. (a) Antenna setup for the testing (b) Closely display of network analyzer screen

Specific absorption rate (SAR): The Specific Absorption Rate (SAR) is the quantity of electromagnetic (EM) energy radiated by an antenna and absorbed in body tissue, divided by the time-domain averaging mass and it is a key statistic for medical applications where the radiation cannot be too high. Typically, SAR values are averaged over a certain mass of tissue (such as 1 or 10 grams) or the whole body. As seen in *table 5*, several countries have set maximum limits for SAR of RF energy that can be emitted from devices to ensure safety and minimize any possible harm due to exposure of electromagnetic/radiation.

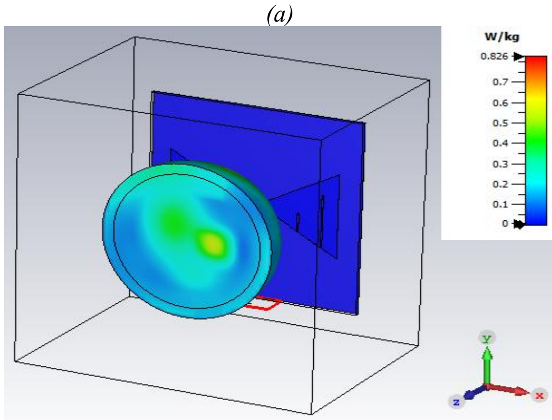
Table 5. Specific absorption levels for different countries

Countries	Association Deciding SAR	SAR Value (W/kg)
India	TEC (Telecom Engineering Center)	1.6 Watts per kilogram (W/kg)
United States	FCC (Federal Communications Commission)	1.6 Watts per kilogram (W/kg)
European Union	CENELEC (European Committee for Electrotechnical Standardization	2.0 Watts per kilogram (W/kg)

IEEE standards state that a low SAR makes it perfect for medical applications. *Figure 16(a)* and *figure 16(b)* display the SAR values of the suggested phantom in the bowtie antenna with and without tumor, respectively. Specific Absorption Rate (SAR) analysis is performed in order to accurately determine the location of tumor within the breast. It is noted that the energy absorbed by the cancerous breast is greater compared to the normal breast thus it helps to find the location of the cancerous tumor with accuracy through finding the coordination of the peak of SAR by Menon & Rodrigues [25].



(a)



(b)

Figure 16. (a) SAR value of proposed bowtie antenna (without tumor) (b) SAR value of proposed bowtie antenna (with tumor)

The proposed simulation environment is used in biomedical research. Consequently, the SAR of the suggested system on breast tissues is investigated. *Figure 16 (b)* shows the SAR of the radiating antenna in the resonant frequency in the presence of a breast phantom. The SAR value is studied when the phantom is directly radiated by the antenna. The antenna is therefore within the safety limits when used by human beings (less than 1.6 W/Kg at 1g) and easily applicable in the proposed biomedical applications as in Das et al. [26]. This procedure is able to easily identify the tumor since the reflection coefficient varies in the presence of a tumor in the breast phantom by Hossain [27]. A comparison of the antenna's surface current, electric field, magnetic field, and SAR value showed in *table 6*.

Table 6. Comparison of Parameters

Phantom model	Electric field (V/m)	Magnetic field (A/m)	Surface current (A/m)	Specific absorption rate (W/kg)	Directivity (dBi)
Without tumor	22800.9	107.39	91.4154	0.792	7.24
With tumor	22773.1	106.934	90.8979	0.826	7.18

With the addition of slits, there is a slight change in the bowtie antenna performance. It has no slits, meaning a high electric field (22800.9 V/m), and a magnetic field (107.39 A/m), as well as a low SAR (0.792 W/kg), which implies efficient radiation. The electric and magnetic fields (106.934 A/m) and the slits reduce the electric and magnetic fields (22773.1 V/m) slightly, and SAR rises to 0.826 W/kg, demonstrating better energy absorption.

Table 7. Comparison with existing literature

References	Resonant frequency (GHz)	Reflection coefficient dB	VSWR	Gain (dBi)
[28]	2.4	-25.44	1.128	--
[29]	2.555	-19.05	1.251	2.16
[30]	2.45	-22.4	1.164	--
[31]	2.45	-17.5	<2	--
[32]	2.885	-12.470129	--	--
[33]	4.452	-29.95	1.065	2.2
This work	5.02	-43.379	1.013	7.18

The *table 7* indicates the difference between the previous work and the present work by VSWR, return loss and gain. The comparative analysis indicates that the present design is much superior to the current literature in all the important antenna measures. With a higher resonant frequency of 5.02 GHz, this work attains a better reflection coefficient of -43.379 dB which means that the impedance matching of the work and signal loss are near perfect as compared to the next best of -29.95 dB in [33]. In addition, the VSWR of 1.013 is close to the theoretical value of VSWR = 1, which provides the greatest power transfer. Most significantly, the suggested antenna has a gain of 7.18 dBi, which is over three times larger than [29] and [33], a significant improvement is observed with the high gain in wireless communication design.

5. CONCLUSION

In this paper, the successful design and simulation of a bowtie antenna using CST Studio Suite software has been presented. The proposed work is superior to the available references because it has a larger resonant frequency of 5.02 GHz, better reflection coefficient (-43.379 dB) and a good match of VSWR (1.013). It also provides maximum gain (7.18 dBi), which is better than previously reported designs in terms of efficiency, return loss and radiation features. The following conclusions can be made after simulation of this proposed bowtie antenna for Sub 6 GHz applications.

(1) A phantom with a tumor is provided with the specific electric field and disturbs the electric field. The simulated E-field without tumor is 22800.9 V/m, however in the presence of the tumor it changes to 22773.1 V/m with distortion.

(2) Tumor bearing phantoms has disrupted magnetic fields. In simulated H-field, phantom without tumor is 107.39 A/m, whereas phantom with tumor distorts it to 106.934 A/m.

(3) High conductivity material, *i.e.* copper and low conductivity dielectric material *i.e.* ε_r enables efficient surface current flow in the absence of tumor. Hence Surface current in phantom without tumor is 91.4154 A/m, whereas phantom with tumor distorts it to 90.8979 A/m.

(4) Tumors increase SAR due to electrical differences with healthy tissues. SAR data are limited to the tumor and environs. In tumor-bearing phantoms, SAR is higher, especially within the tumor. Thus, simulated SAR in phantom without tumor is 0.792 W/1kg and increases to 0.826 W/1kg in phantom with tumor.

(5) The bowtie antenna's specified radiation pattern is characterized by its far field directivity of 7.24 dBi at 5 GHz in phantom without tumor and 7.18 dBi in phantom with tumor.

The slits are introduced in order to increase the electromagnetic interaction and prove that the antenna design is efficient, sensitive and can be used in biomedical detection applications.

The simulated and measured results were close to each other and significant improvements in return loss, VSWR, and gain were received to confirm the validity and reliability of the proposed design. Thus, an attractive and practically viable antenna in future generation portable wireless system applications in the fields of IoT and healthcare is offered.

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