A Planar On-Body Antenna System for Cancerous Tumor Detection through Microwave Transmission Sensing

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Abstract: *A two antenna based detection model is studied in order to investigate the change of the dielectric properties of human tissue in the presence of a malignant tumor. Microwave transmission is evaluated through a direct comparison with a reference value and initial numerical results for various tumor sizes, demonstrate that the system may be used for future early detection of the presence and position of tissue abnormalities.*

Keywords: *Microwave radiometry, microwave sensing, skin depth, spiral antenna, S-parameters.*

1. Introduction.

Microwave imaging has been proposed to detect and diagnose malignant tissue, to monitor health and to assess human tissue density [1 - 3]. An antenna system designed for biomedical sensing is meant to operate in contact with a lossy medium, such as the human tissue. The antenna of such a system is placed close to the human body, so the effective wavelength deviates from the free space wavelength. This leads to loss of impedance matching, a fact that translates into additional losses in the microwave sensing system. As a result, a number of recent studies are directed to utilize an ultra-wideband (UWB) antenna [4-12], [14] that covers all the frequencies of interest and the adjacent spectrum areas in order to always perform nominally. In this paper, a spiral antenna system is proposed that maintains UWB operability and is shown to exhibit good matching properties in contact with human body tissue.

The proposed antenna system is designed to operate within the frequency region of 1-5 GHz. According to previous studies [4-5] the frequency of operation allows for the detection of tissue anomalies in various depths in the human body, depending on the skin depth of each frequency. The skin depth gives a measure of the average depth of penetration of the electromagnetic field. In low frequencies, the permittivity is relatively high and thus the conductivity is low, and the electromagnetic wave can propagate through the tissues without too much attenuation shown that the proposed frequency range is sufficient in order to measure several cm below skin surface.

In this work two different human torso models are considered. Initially, a simple model that consists of a rectangular box with dimensions 20 x 20 x 40 cm^3 is used, in order to demonstrate the feasibility of the concept and provide early results of the proposed spiral antenna system. Then, a more detailed layered model using elliptical cylinders to model the human torso [15] is used and the corresponding results are presented. Numerical results are obtained for various tumor sizes, demonstrating that the proposed system may be used for future early of the position and size of tissue anomalies.

2. Proposed Procedure For The Detection Of Tumor Position And Size

In this work, an antenna system model is proposed, which consists of two identical spiral antennas. The system is designed to operate in two distinct modes: Passive mode, in which radiometric measurements are planned to be used in the future to detect the depth of the abnormality, and active mode, in which using the alteration of the transmission coefficients is providing the ability to detect the size of the tumor.

The proposed system under evaluation was generated and simulated with CST Microwave Studio software suite.

A. Passive Mode – Tumor depth detection through microwave radiometry

The proposed on-body antenna system is intended (in passive mode) for radiometric measurements few centimeters below the human skin. An important parameter, which is essential when studying electromagnetic propagation in a material, is the skin depth, which is given by:

$$\delta_m = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (1)$$

By using microwave radiometry, the power level of thermal radiation from a tissue region can be captured and it is dependent on the skin depth. The outer radius of an antenna's near field is given by:

Table 1
Skin Depth in Human Fat – Near Field Radii

Conductivity (S/m) 1217	Frequency (GHz)	Skin Depth (cm)	Reactive Near Field Outer Radius (cm) Short Case	Near Field Outer Radius (cm) Long Case
0.052824198	1.0	6.9	4.8	-
0.076407383	1.5	4.7	4.4	-
0.10612505	2.0	3.5	-	5.1
0.140677343	2.5	2.7	-	5.7
0.178888811	3.0	2.2	-	6.2
0.26229974	4.0	1.6	-	7.2
0.34981792	5.0	1.2	-	8.0

$$\left.\begin{aligned} R_{near\ field} &= 0.62\times\sqrt{\frac{D^3}{\lambda}},\ D>\frac{\lambda}{2}\left(\text{electrically large antennas}\right) \\ R_{near\ field} &= \frac{\lambda}{2\pi},\qquad D<\frac{\lambda}{2}\left(\text{electrically small antennas}\right)\end{aligned}\right\} \quad (2)$$

For example in the case of breast tumor detection, from equation (1) is clear that maximum skin depth (for human fat) results to a minimum frequency for desired application of 1 GHz as depicted in Table 1.

For the frequency range from 1 GHz to 1.5 GHz the antenna is considered electrically short while in the 1.5-5 GHz range is considered electrically long (total antenna length D=10 cm).

So it is clear, as presented in Table 1 that the aforementioned measurements are well in the radiative near field of the electrically short antenna, for frequencies up to 1.5 GHz while for the remaining frequency range the electrically long antenna measurements are in the Fresnel Zone.

A crucial parameter is the detection range of the antenna which depends on the operating frequency and skin depth, indicating the distance of the radiation propagated in a lossy medium.

The detection range (R) of the antenna is calculated as:

$$\left.\begin{aligned} R_{short} &= \text{Re}\,active\ Near\ Field\ Radius + Skin\ Depth \\ R_{long} &= Near\ Field\ Radius + Skin\ Depth\end{aligned}\right\} \quad (3)$$

and presented in Table 2 for various frequencies.

Table 2
Antenna Detection Range per Frequency

Frequency (GHz)	Detection Range - R (cm)
1.0	4.8-11.7
1.5	4.4-9.1
2.0	5.1-8.6
2.5	5.7-8.4
3.0	6.2-8.4
4.0	7.2-8.8
5.0	8.0-9.2

B. Active Mode – Impact of Tumor size on antenna coupling measurement

The two spiral antennas system presented herein is proposed to radiate directly into a dielectric medium (human body model); in each scan process, one antenna is used as the transmitter and the other acts as the receiver.

The scattered field of the tumor can be calculated by subtracting the incident field (background field) from the total field [15]. Here the incident field means the electromagnetic field generated by one antenna radiation in dielectric medium when there is no tumor, while the total field is the corresponding field when a tumor exists. So the S_{21} parameter, which depends on signal transmission and reception, can be used to represent the detection capability. The tumor diameter change is detectable by the change of the S_{21} parameter magnitude. For simplicity, we assume that the tumor is spherical and located at the center point between the two antennas. We show that the increase of the tumor size is directly related to the decrease of the S_{21} magnitude within the entire operating region. Thus, this information can be used for estimating the size of the tumor.

3. Antenna System Architecture and Human Body Model

The antenna system that was used, according to the concept discussed in the previous Section, consists of two spiral antennas located in opposite sides across the human body (torso). Fig. 1 depicts a sample layout of the proposed antenna system with a simple human body model phantom of dimensions 20 x 20 x 40 cm^3 and electrical characteristics that correspond to human fat (dielectric constant $\varepsilon_r = 5.2323$, conductivity σ=0.10612 S/m, at 2GHz) [12],[16-17].

The proposed antennas have been designed aiming at future development using textile materials [13]. Each of the identical antennas is an implementation of a typical spiral design and is depicted in Fig. 2. It consists of a fixed 0.1 cm width wire with a linear radius increment factor equal to 0.6π cm per full rotation. The initial spiral radius is equal to 2.05 cm and each spiral branch extends for a total rotation of 13 rad. The gain of the antenna across the frequency band of operation is presented in Fig. 5.

The reflection and transmission coefficients of the antenna system (S_{11} and S_{21}) are displayed in Fig. 3 and Fig. 4 respectively.

Moreover, Fig. 3 and Fig. 4 also illustrate the reflection and transmission coefficients of the two antennas placed at a distance of 40 cm to each other without the presence of any human body model, as well as the reflection and transmission coefficients of the two antennas in the case where a more accurate human body model of elliptical cylinders is used.

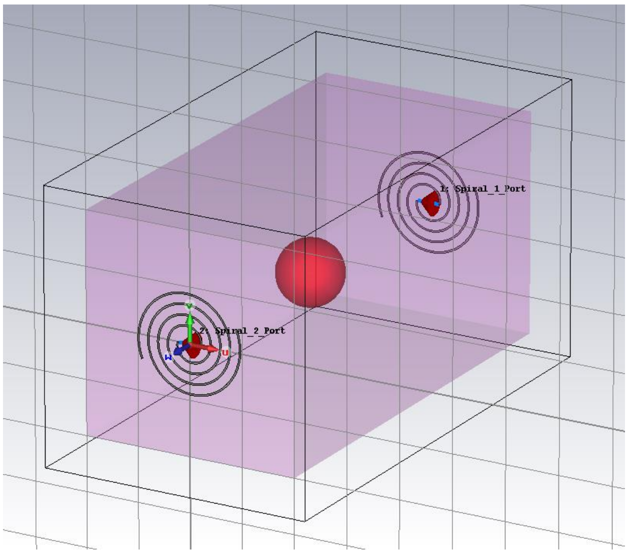

Fig. 1. Spiral antenna system with simple human body model in the presence of a cancerous tumor (sphere)

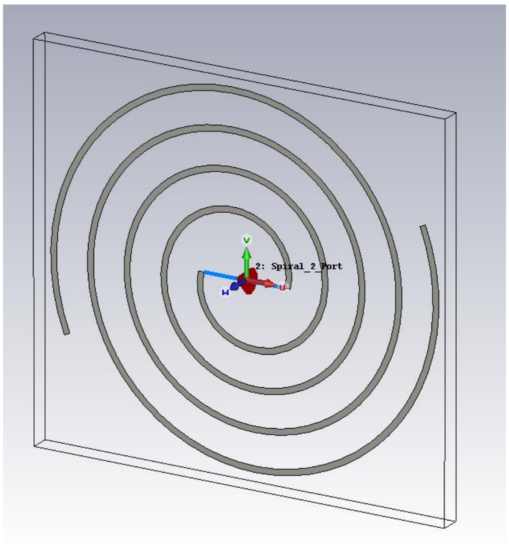

Fig. 2. The Spiral antenna

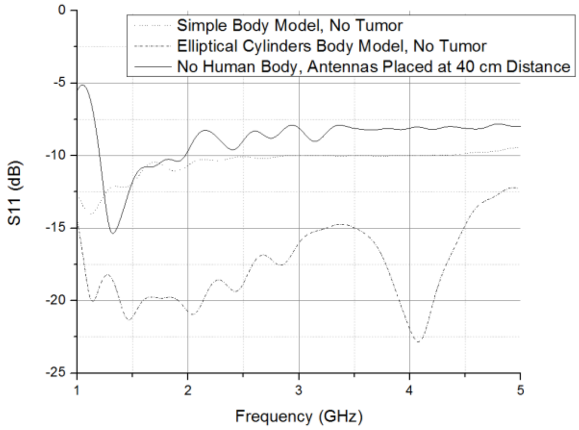

Fig. 3. Reflection coefficient of spiral antenna with/ without human body models.

The elliptical cylinders human body model, depicted in Fig. 6, is considered to be much more detailed compared to the simple box illustrated in Fig. 1. The elliptical body model consists of a total of five layered elliptical cylinders of 40 cm height each; every cylinder corresponds to a different human body area. From outermost (Skin) to innermost (Internal Organs) cylinder the materials, dimensions and electrical characteristics are presented in Table 3.

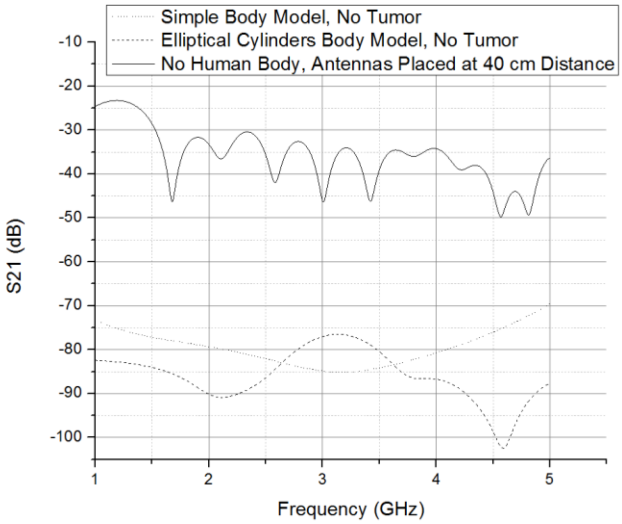

Fig. 4. Transmission coefficient between spiral antennas with / without human body models at 40 cm distance, with Elliptical Cylinders body model (at 16.8 cm distance)

The two spiral antennas are attached across the body model at the mid-height of the skin cylinder and are facing one another. It is interesting to notice that, according to the results of the input reflection coefficient of the spiral antennas presented in Fig. 3, the reflection coefficient of the proposed spiral antennas is slightly improved when the antenna is attached to the simplified body model, but significantly improved when the antenna is attached to the detailed elliptical cylinders model.

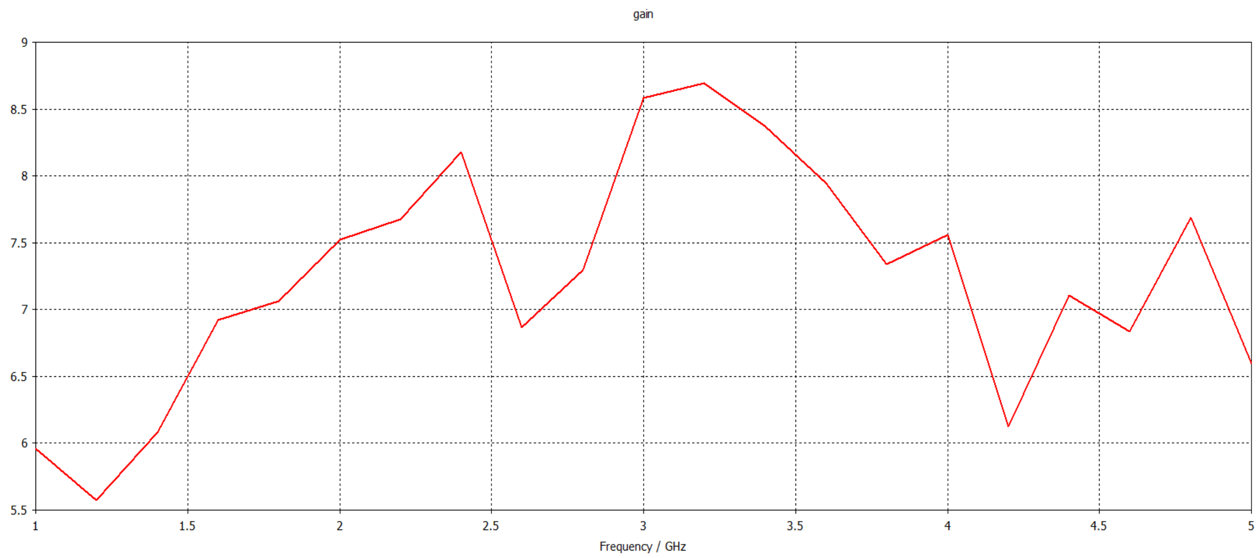

Fig. 5. Gain Values over the Operating Frequency Band (1-5 GHz) of the Spiral Antenna

This results indicates that the proposed UWB antenna is appropriate for operation in contact with the human body.

Moreover, according to the proposed procedure for tumor size detection in Section 2, the results presented in Fig. 4 (transmission coefficients) will act as the reference base for transmission measurements in the case where no tumor is present. In comparison, numerical results for the transmission coefficients in the case where a tumor of variable size is present are collected and presented in Section 4.

4. Effect of Tumor Size on Antenna System Transmission Coefficient Magnitude

The presence of a tumor inside the human body model effectively alters the S_{21} response of the antenna system. Fig. 77 illustrates this response in the case of the simple human body model within the 1-5 GHz frequency range. The propagation environment exhibits a larger transmission attenuation within a tuning frequency region centered at around 3.2 GHz without tumor present and shifting to around 3 GHz with a tumor (ε_r = 53.81, conductivity σ=2.799 S/m, at 2.45 GHz) present.

Furthermore, the S_{21} magnitude drops at the tuning frequency for more than 6 dB from no tumor to a 3 cm tumor size (from -85 dB without tumor to -91 dB with a tumor of radius 3 cm). This significant change in the S_{21} magnitude can be used as an indicator of a tissue anomaly that could potentially be due to the presence of a tumor. It is noted that the S_{21} magnitude exhibits a reverse trend and increases with tumor size in the region below 1.8 GHz; this behavior is not considered to affect the usability of the proposed technique.

Furthermore, Fig. 8 illustrates the effect of a tumor on the S_{21} response of the antenna system in the case of the elliptical cylinders human body model.

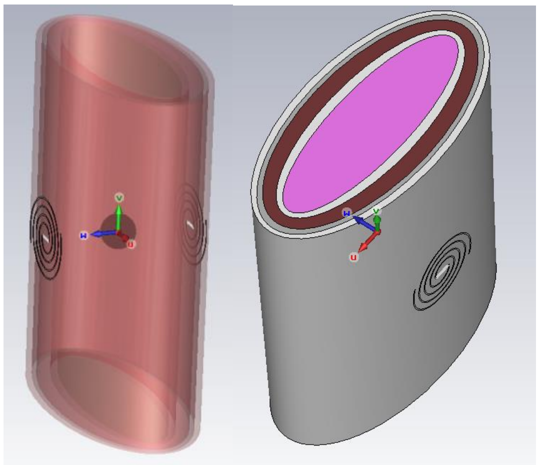

Fig. 6. Spiral antennas system with elliptical cylinders human body model in the presence of a cancerous tumor (sphere)

In this case, the frequency response of the system is more complicated; Fig. 8 indicates the presence of two different tuning frequencies that both shift with the presence of the tumor. The S_{21} magnitude still decreases with tumor presence but is virtually unaffected with tumor size.

The S_{21} magnitude decrease is more severe at the 4.5-5 GHz frequency range, with a peak drop of 11 dB (from -103 dB at 4.6 GHz for no tumor presence to -114 dB at 4.9 GHz with a tumor of 3 cm radius).

Table 3
Elliptical Cylinders Human Body Model Layer Electrical Characteristics [12], [16-17].

Layer Material	Major Diameter (cm)	Minor Diameter (cm)	ε_r	Conductivity (S/m)
Skin	33.5	16.8	38.57	1.265
Fat	32.5	15.2	5.33	0.086
Muscle	31	14.2	53.29	1.4538
Bone	28.4	10.5	11.65	0.310
Internal Organs	27.2	8.4	53.38	1.912

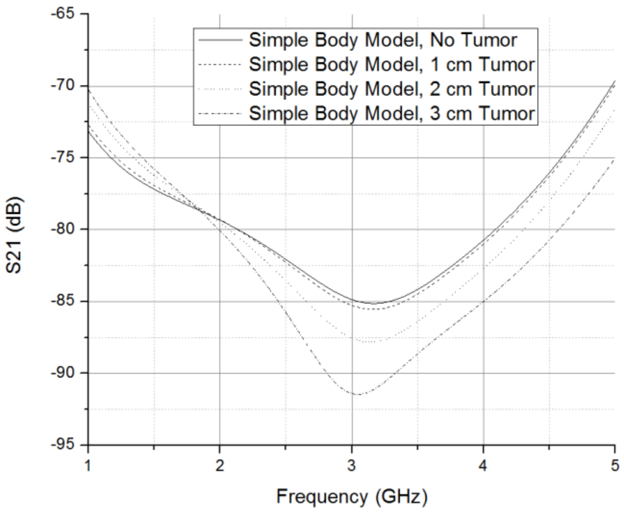

Fig. 7. Transmission coefficient with the simple human body model without tumor presence or with a tumor placed at equi-distance between the two spiral antennas and with a radius of either 1 cm, 2 cm or 3 cm

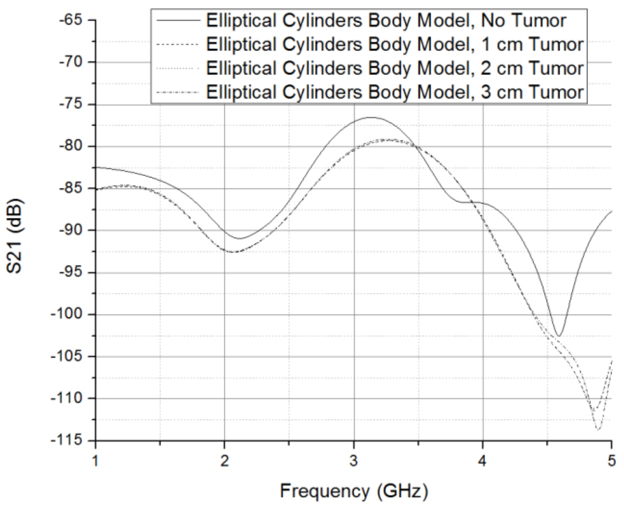

Fig. 8. Transmission coefficient with the elliptical cylinders human body model without tumor presence, or with a tumor placed at equi-distance between the two spiral antennas and with a radius of either: 1 cm, 2 cm or 3 cm

5. Conclusions

A microwave transmission coefficient sensing system of two spiral antennas is proposed herein for early detection of the size of a tumor. Numerical results indicate that in two human body models (simplified human model, multi layered human body model) the proposed antenna system is capable of detecting an abnormality (cancerous tumor) of radius 1 – 3 cm.

As it is depicted in the transmission coefficient (S_{21}) of the simplified model, the difference between no tumor and a tumor of 1 cm is 3 dB; this level of S_{21} change is considered to be high enough for tumor detection in relevant applications. Ongoing work is being conducted to thoroughly simulate the system behavior for various tumor positions and to build appropriate antenna array integrated in the human tissue mimicking phantom material, and perform experiments to validate the feasibility of the imaging system we proposed. Furthermore, the radiometric features of the proposed antenna system are being assessed, in order to evaluate its potential for future use as a means to detect the position of the tumor.

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