Design of UWB Compact Slotted Monopole Antenna for Breast Cancer Detection

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Abstract

This work presents the design of an UWB Microstrip antenna for microwave imaging systems aimed for breast cancer detection. The localization coordinates of the tumor are studied in detail for better tumor detection. The coordinates of the corresponding maximum value of SAR are identified in order to accurately detect different locations of tumor inside the breast. The results show that relying on these coordinates; the tumor can be detected with high accuracy. The possibility of mutual interferences with other systems operating at the FCC frequency band is considered as a major issue in UWB systems. Therefore, rejected out-band interference signals is introduced by etching single and double U-shaped slots on the radiating element, then a first and second frequency band are successfully produced respectively. The proposed antenna is a compact antenna that can be used on microwave imaging detection. The antenna gain was larger than 2 dBi with an omnidirectional radiation pattern over the whole frequency-band. A relatively flat group delay of the antenna response is also achieved. Antenna prototype has been manufactured and measured; results prove the performance of the proposed antenna.

1. Introduction

Breast cancer is the most common cancer in women worldwide and the breast cancer is the most common cancer in women worldwide and the second most common cancer overall. However, the detection of cancer at early stages reduces mortality and can enhance survival rates [1]. A number of screening techniques have been clinically employed, including X-ray Mammography, ultrasound and Magnetic Resonance Imaging (MRI). However these techniques suffer from a number of limitations [2][3]. In response to these challenges, it has resulted in research into alternative methods for imaging breast cancer. A number of research groups suggested the use of UWB microwave imaging technique, which aims to exploit the dielectric-properties contrast between normal fatty breast tissue and malignant tumors [4]. The technique has many advantages in comparison to other breast cancer detection techniques. It gives better result with the main advantage of using non-ionizing radiation, it has the potential to be both sensitive and specific, to detect small tumors, and to be less expensive. In addition, this technique involves minimal discomfort to patients, which makes the procedure acceptable to women [5]. Due to its multiple advantages, this technique has already been implemented by different research groups. The first time-domain UWB breast cancer detection system has been described in [6]. The second generation of this system [7] has been assembled for clinical trials. The research group at McGill University has developed and advanced an experimental multistatic hemispherical microwave breast imaging system based on time-domain measurements [8,9]. The system has been tested on volunteers and prepared for clinical trials. The UWB system is a high data transmission-rate wireless communication system which operates in the frequencies between 3.1 to 10.6 GHz. However, some other coexisting wireless technologies such as WiMAX (3.4 3.94 GHz) and WLAN (5.42 6.15 GHz) may interfere with the Federal Communications Commission (FCC) UWB RF spectrum, which negatively affect its intended functions [10]. Thus, removing this type of interference is considered as a crucial issue in designing UWB system. In some cases, UWB antennas use filters to avoid interferences. However, the use of filters increases the complexity and cost of the system [11, 12]. Therefore, it is advantageous to find some solutions to face these interferences. This article presents a breast tumor detection system based on a compact microstrip antenna. The proposed antenna consists of combining a rectangular patch with microstrip line feeding and a modified ground plane. The deployment of the modified ground plane of the antenna and the use of a U-DMS technique improves the bandwidth and suppress the undesired out-band interference signals respectively [13]. The antenna gain was larger than 2 dBi with an omnidirectional radiation pattern over the whole frequency-band. In addition, the antenna reveals a very low distortion, which is less than 1ns across the band of interest. Mutual interferences can be considered as major issue in UWB systems. To avoid interactions of the designed system with other systems operating in the FCC UWB RF spectrum, a simple technique has been introduced to eliminate the possibility of mutual interferences. This technique is based on etching single and double U-shaped slots on the radiation patch producing a first and second frequency band respectively, and significant reduction of interference with the FCC band can be obtained. The measured VSWR and peak gain of the fabricated prototype with band notch characteristics at 3.4-3.94 and 5.42-6.15 GHz are presented and compared with those obtained by simulations. Both the simulation and measurement results show a reasonable agreement between them. The antenna developed is integrated with the breast model for cancer detection. The most representative breast model developed by the Computational Electromagnetic group of Wisconsin has been taken into account. The localization coordinates of the tumor are studied in detail for better tumor detection. The coordinates of the corresponding maximum value of Specific Absorption Rate (SAR) are identified in order to accurately detect different locations of tumor inside the breast. The results show that relying on these coordinates; the tumor can be detected with high accuracy. The simulation process of the proposed antenna and the breast model was performed using the commercial CST Microwave Studio (Time Domain solver) simulator.

2. Antenna Configuration

We first consider a design operating at the FCC band presented in Fig. 1(a). In this study, we consider the geometry of the proposed conventional monopole antenna without slots. The proposed design approach was printed on low cost FR4 substrate material with relative dielectric constant of 4.4, loss tangent of 0.02, and thickness of 1.6 mm. The proposed antenna consists of one radiator which is placed on the top of the dielectric substrate and is feeded by a strip-line of 50 Ω.

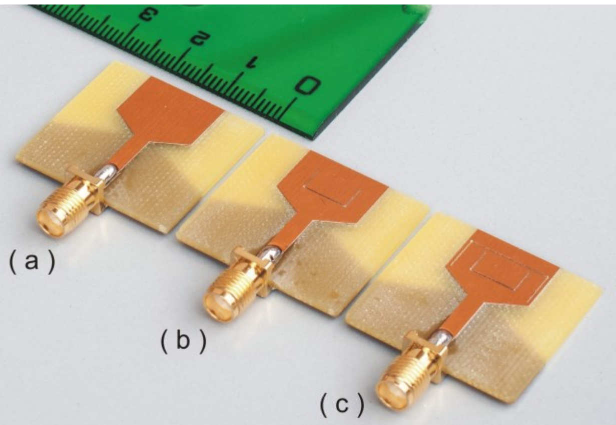


Figure 1: Photo of the fabricated prototypes :(a) no slot, (b) single slot coexisting frequency bands", (c) dual notch antenna.

The corresponding results are plotted in Fig. 3. It can be shown that the antenna can operate through an impedance bandwidth spreading from 3.6 to 11 GHz with a VSWR less than two. In order to overcome the unwanted interferences of UWB communication systems with coexisting frequency bands, various methods have been proposed [14, 15]. In this paper, we include a U-DMS technique as one of the simple, effective, and inexpensive methods [16]. To obtain a stop-band filtering property, a notch frequency can be found as per (1):

$$f_{notched}=c/2L\,(\varepsilon_{re})^{0.5} \qquad (1)$$

where L is the total length of the slot, ε_{re} is the relative effective dielectric constant and c is the speed of light. For a dielectric substrate with thickness h, a microstrip line with width w, and relative permittivity of ε_{re}, the effective permittivity can be found by (2):

$$\varepsilon_{re}=0.5\,[(\varepsilon_r+1)+(\varepsilon_r-1)(1+12h/w)^{-0.5}] \qquad (2)$$

By embedding one U-shaped slot in the radiating patch, as shown in Fig. 1(b), a single stop band of 5.425 6.150GHz was achieved. This notched band reduces the interferences from both the IEEE 802.11a and HIPERLAN/2-WLAN systems. Besides HIPERLAN/2-WLAN systems, WiMAX operating from 3.375 to 3.945GHz may cause interferences to the UWB system too.

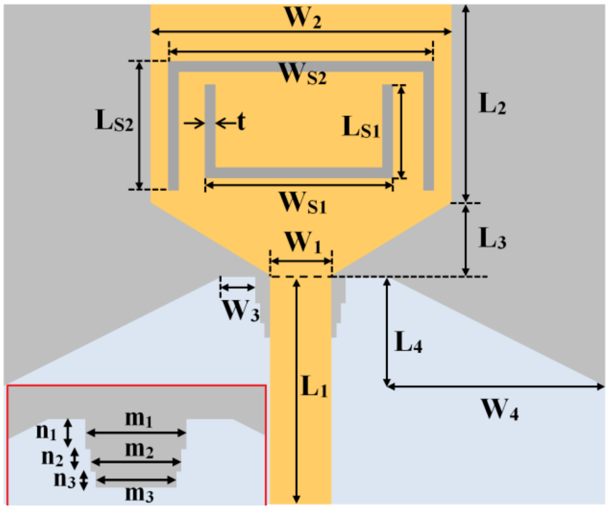


Figure 2: Dual band-notched UWB antenna characteristics with detail of ground plane.

In order to achieve band-notched function, we implement an opposite U-shaped slot without affecting the first stop band. Fig. 1(c) shows the geometry of the antenna. The top view of this antenna and the slots on the ground plane is given in Fig. 2. Note that, the width of the U-shaped slot and the ground plane slot determine respectively the bandwidth of the rejected band. The geometry parameters of the dual-band notched UWB antenna design are: L_1=13.5 mm, L_2=9.5 mm, L_3=3 mm, L_4= 26 mm,W_1=2.8 mm, W_2=14 mm, W_3=2.02 mm, W_4=28 mm, n_1=0.96 mm, n_2=0.74 mm, n_3=0.45 mm, m_1=3.96 mm,m_2=3.19 mm, m_3=3.02 mm, Ls_1=4.5 mm,

Ls_2=6 mm,W_{S1}=7.3 mm, W_{S2}=13 mm and t=0.2 mm. In Fig. 1, it is shown a photo of three built prototypes: without notched-bands, single notched band, and dual notched bands, from left to right. The antenna physical dimensions correspond to an electrical size of 0.25λ. For measurements, a 50Ω SMA was connected to the feed line.

3. Results and Discussion

The radiation pattern of the antenna with dual band-notched characteristic is presented in Fig. 4. It is observed an omnidirectional performance in the H-plane, and a like-small dipole in the E-plane.

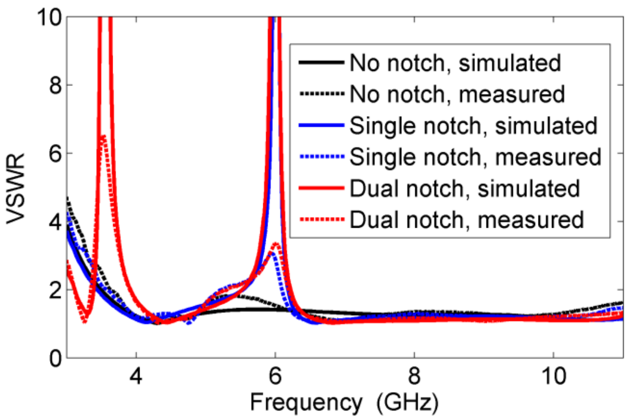
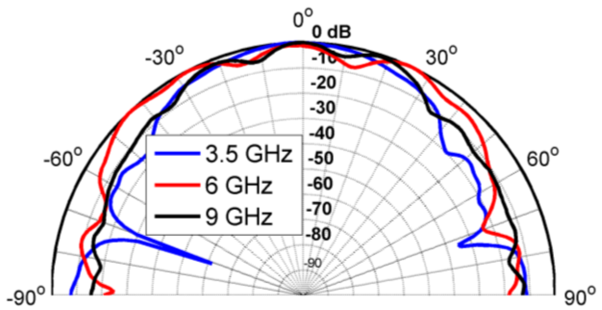
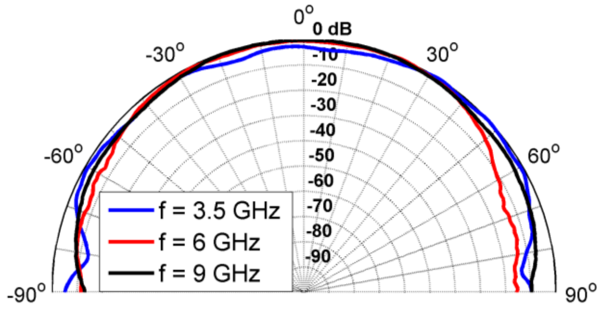


Figure 3: Comparison of simulated and measured VSWR.

The gain was measured in an anechoic chamber with the method of the three antennas, in two steps: first, two rectangular horn antennas are used, and then a horn is replaced by the antenna under test. The s21 (f) obtained in the second step is divided by the s21 (f) of the first step, in natural units. Traces s21 (f) are complex and measured with VNA. Previously, a pass-through calibration has been carried out that includes VNA and cables to subtract its effect from the s21 (f) traces obtained. In Fig. 5, we plot the antenna gain for the three built prototypes. The gain is over 2 dBi for the entire band with a deviation of 2.5 dB for the three cases, so resulting in a flat frequency response, considering the ratio of gain flatness versus bandwidth.



(a)



(b)

Figure 4: Radiation pattern for double notched antenna design: (a) E-plane at 3.5, 6, and 9 GHz. (b) H-plane at 3.5,6, and 9 GHz.

Fig. 6 illustrates the current distributions at 3.4 GHz and 5.5 GHz within the two notch band. As can be seen, the current is intensively concentrated around the outer slot and the inner slot respectively, which proves that the inductive coupling between the U-DMS does not affect strongly the antenna characteristics. On the other hand, the current circulation on the two U-slots presents two null of current. These nulls correspond to the first and the second modes created by the slot shapes around the frequency of 3.4 GHz and 5.5 GHz.

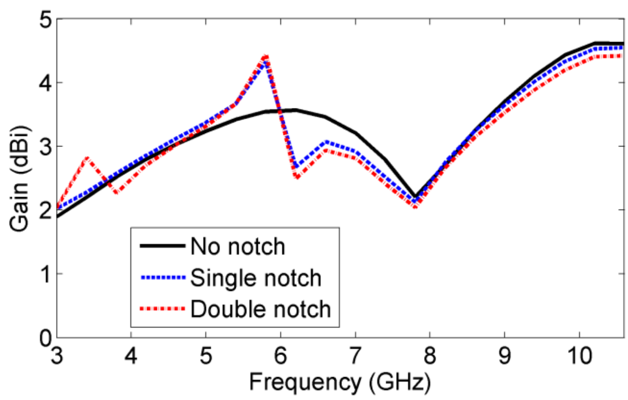
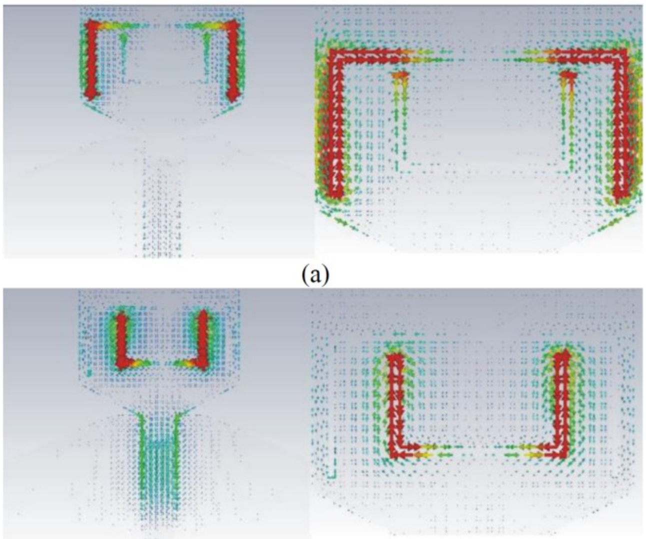


Figure 5: Antenna gain comparison.

Consequently, the radiation behavior of the conventional antenna has been affected by the first and the second frequency modes corresponding to the U-slots. The circulation of the distribution of the current on the edge of the U-DMS demonstrates that radiation losses; due to the step discontinuities; will not introduce an anomalous behavior in the radiation patterns.



(a)

(b)

Figure 6: Current distribution of the proposed dual-notch antenna at (a) 3.4 GHz and (b) 5.5 GHz.

Group delay is an important parameter in the design of the UWB antenna as it measures the distortion of the pulse signal in time domain. For a good pulse transmission, it is desired that the group delay response is stable over the UWB frequency band [17]. Two identical antennas are arranged face to face at a distance of 40 mm. Group delay of the proposed antenna is depicted in Fig. 7. It is observed that the group delay reveals a very low distortion, which is less than 1 ns across the entire UWB band. However, at the center frequency of the notched band, the maximum group delay exceeds 6 ns. The characteristic of the group delay indicates that the antenna exhibits good phase linearity at entire UWB band except at notched band with no distortion signal between transmitting and receiving.

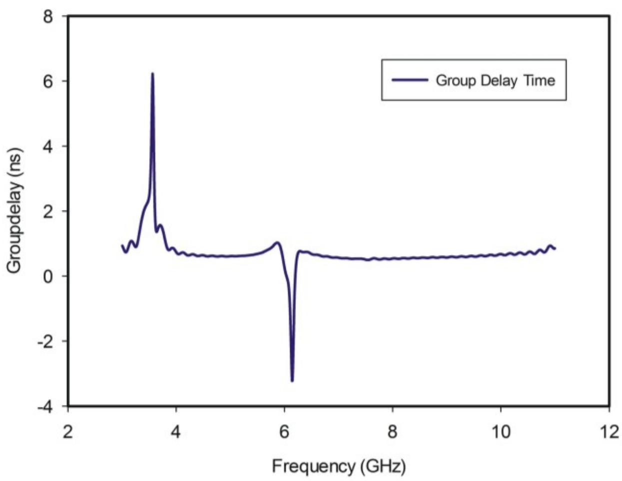


Figure 7: Simulated group delay of the proposed antenna.

4. Breast detection model

Several breast models have been proposed and evaluated over the past few years to predict risk of breast cancer. In fact, many studies have indicated that the electrical properties of breast tumors are significantly different from those of healthy breast tissues [18][19].

Table 1: SAR exposure limits in different environments

	SAR_{wb}	SAR_{1g}	SAR_{10g}
Controlled Environment	0.4	8	20
Uncontrolled Environment	0.08	1.6	4

To demonstrate the performance of the designed antenna in breast cancer detection, the proposed antenna is applied to a microwave imaging system. Fig. 8 illustrates the simulation system including the heterogeneous breast model and the proposed notch antenna.

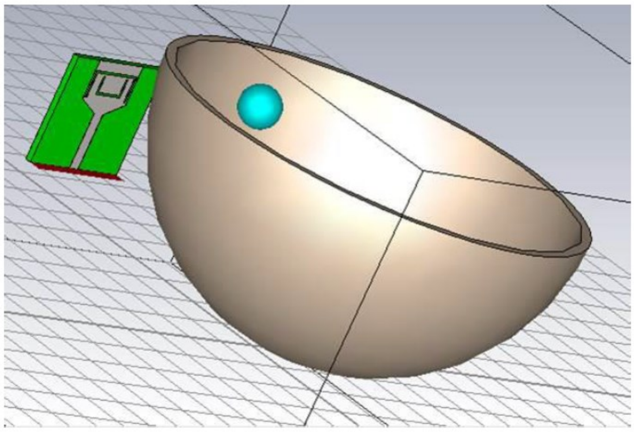


Figure 8: Heterogeneous breast model with the proposed antenna.

In the hemispherical utilized model, the skin layer is assumed to have a thickness of 2 mm, a dielectric constant of 37 and a conductivity of 1.1 S/m. The tumor included in the breast model is a sphere with 5 mm radius and has the dielectric properties close to a real tumor: a dielectric constant of 50 and a conductivity of 4 S/m. The distance between the antenna and the model is kept at 10 mm.

The interaction of electromagnetic waves with biological tissues results in energy absorption. In fact, electromagnetic waves radiated from the transmitting antenna directly travel through the patients breast and significant portion of the radiated power carrying by electromagnetic waves is absorbed by breast tissues The absorption per unit mass of the tissue is estimated with SAR and can be determined by (3):

$$SAR = \sigma\left(\frac{|E|^2}{\rho}\right), \quad (3)$$

Where SAR is the Specific Absorption Rate (W/Kg), σ is the conductivity (S/m) of the tissue, E is the internal electric field (V/m) and ρ is the mass density (Kg/m^3).
A brief exposure to radiation may cause severe health hazard. Because of that, the amount of SAR induced inside human breast is an important feature of any microwave breast imaging system. Table 1 shows the limits for the

Table 2: The detection of the tumor at three different frequencies 5, 7 and 8 GHz according to the maximum value of SAR.

	Frequency (GHz)					
	5		7		8	
Actual Position of Tumor at (x,y,z)	Max SAR(W/KG)	Max at (x,y,z)	Max SAR(W/KG)	Max at (x,y,z)	Max SAR(W/KG)	Max at (x,y,z)
(6,40,15)	1.4748	9.68, 39.53, 12.18	1.0967	9.68,42.18, 12.18	1.1632	2.68, 42.18, 12.18
(10,58,39)	9.2064	6.95, 53.78, 20.08	23.1560	13.45,60.18, 34.78	18.213	20.33,60.18, 34.78
(-5 ,48,25)	2.1258	-0.78, 50.81, 24.21	2.3862	-4.53, 49.56, 22.81	2.707	-4.53, 50.81, 27.81

local SAR values that is averaged over the whole-body SAR_{wb}, 1g of tissue (1G), or 10g of tissue (10G) under different environments [20].

The utilized SAR values in this work fall below the maximum standard SAR limit, which ensures the safety of our proposed microwave breast imaging system. Table 2 shows the detection of the tumor at three different frequencies 5, 7 and 8 GHz according to the maximum value of SAR. The tumor is located at multiple different positions. It is observed that the coordinates of maximum value of SAR actually point to the position of the tumor at all studied frequencies. This indicates that the maximum local SAR distributions occur in the tumor.

5. Conclusions

In this article, the development of a compact UWB antenna for microwave breast cancer imaging has been proposed. The geometry of the achieved UWB antenna design is simple with compact size and minimal critical parameters. The proposed antenna shows an omnidirectional radiation patterns, stable peak gain, and a small group delay across the whole UWB frequency range. A simple technique to reduce interferences with other systems operating on the FCC band has been also proposed. Antenna prototype has been manufactured, good agreements are achieved with the simulations. The designed antenna can be considered as a good candidate for microwave imaging detection. A model representing the main tissues of the human breast has been developed. The coordinates of the corresponding maximum value of SAR are identified in order to accurately detect different locations of tumor inside the breast. The results show that relying on these coordinates; the tumor can be detected with high accuracy. The efficient localization of the tumor proves the validity of the entire system developed in this work.

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