Microstrip Back-Cavity Hilbert Fractal Antenna for Experimental Detection of Breast Tumors

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***Abstract*— This paper presents a miniaturized microstrip back-cavity Hilbert Fractal Antenna specifically designed for breast cancer detection. This antenna is used to investigate on the possibility of detecting the presence of breast tumors by directly measuring the shift of the antenna resonance frequency. First, simulations are performed on a multi-layer breast model; then the proposed approach was applied for *in vivo* measurements on two different patients diagnosed with breast cancer, followed by *ex vivo* characterization of the electrical properties of excised tumors.**

Keywords—back-cavity, Hilbert Fractal Antenna, breast tumor, *in vivo*, *ex vivo*.

I. Introduction

Breast cancer is one of the leading causes of women mortality [1] and, premature diagnosis and treatment is considered the best hope for surviving from this disease [2-4]. Different techniques are available to detect breast cancer, e.g., X-ray mammography, ultrasonography, Magnetic Resonance Imaging (MRI), microwave imaging etc. The most important ones are ultrasonography and magnetic resonance imaging (MRI), but no one of these methods is used in routine cancer screening. These methods cannot detect the early signs of cancers; they therefore have importance in later diagnostics to verify the malignity of the breast tissues [5-7]. Moreover, inhomogeneities in breast tissues are sometimes erroneously considered malignant in mammograms. Microwave Imaging (MI) and microwave detection methods promise a highly effective complementary technique as the associated systems can be fabricated cost-effectively enabling widespread availability. In particular, microwave detection for frequent breast monitoring would provide a safe, comfortable technique that could help increasing early-stage tumor detection rates. The measurement protocol proposed in this paper consists in detecting a shift of the antenna resonance frequency [8] due to the high permittivity of the tumor. Thus, the antenna is considered as the key element in the RF front-end for the proposed microwave detection system. In this paper, the antenna design focuses first on its compactness which is required to facilitate its placement and manipulation around the breast and to restrict the targeted area and also on increasing the wave penetration in the body to emphasize the influence of the malignant area on the response.

This paper is organized as follows: the breast tissues model used in the study is presented in section II, the antenna design and simulations results are described in section III. Section IV presents *in vivo* measurements on different patients with breast cancer diagnosis and *ex vivo* characterization of the electrical properties of excised tumors. Finally, the paper ends with the conclusion and future work.

II. Breast Phantom Model

As a preliminary, female breast phantom model in this investigation is designed as a simple four layers stacked model as shown in Fig.1. Table1 shows the properties, i.e. electrical permittivity and conductivity at 2.45 GHz [9-12] and thicknesses experienced in average for each tissue layer.

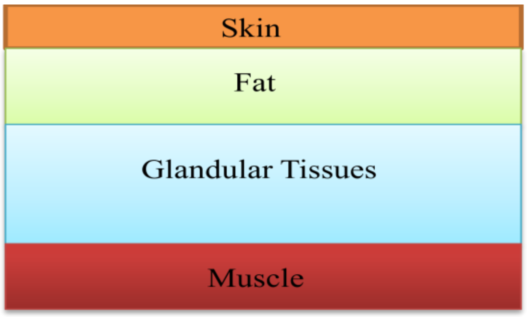


Fig. 1. Brest phantom model.

TABLE I. ELECTRICAL PROPERTIES OF BREAST LAYERS

Tissue	ε_r	σ(S/m)	Thickness (mm)
Skin	38	1.46	1.5
Fat	5.2	0.1	10
Glandular Tissues	20.1	0.5	20
Muscle	52.4	1.91	5

III. ANTENNA DESIGN AND SIMULATION RESULTS

Due to its compactness, a Hilbert Fractal Antenna (HFA) is chosen for the initial antenna design [13]. The antenna dimensions and shape are optimized using CST microwave studio software. The final antenna geometry together with dimensions and characteristics are shown in figure 2(a). The back side of the antenna consists of a partial ground plane of 2.5mm width (Fig. 2(b)). The antenna was designed to operate at 2.45 GHz in the air since this frequency is in ISM (Industrial, Scientific and Medical) band where the signal attenuation in human body is quite small. However, when the designed antenna is positioned in direct contact on the breast skin, the resonance frequency is down-shifted and the antenna's radiation pattern is deformed. The simulations were performed using open boundary conditions.

Indeed, the gain and the directivity, as expected, decreased due to the interaction antenna-body. The breast is a lossy medium with a high permittivity compared to the air (the first layer, i.e. for the skin, ε_r=38), which implies that an important part of the incident wave is back-reflected.

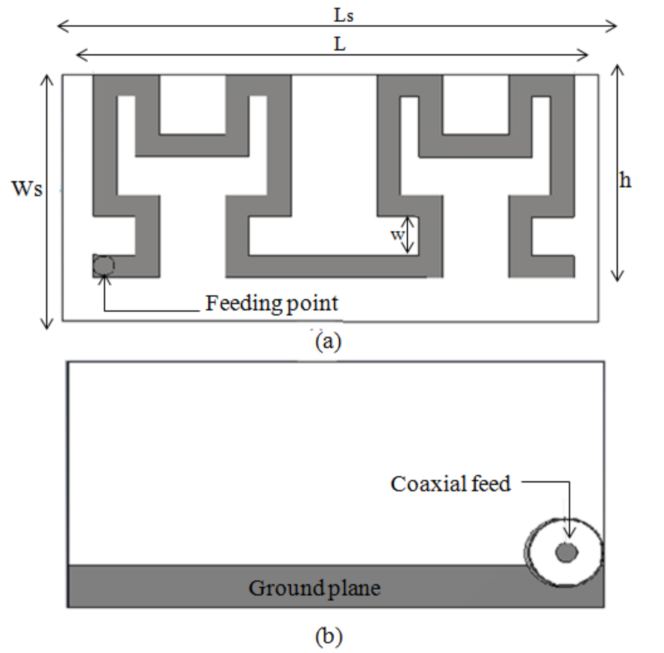


Fig. 2. Antenna geometry: (a) top view, (b) bottom view, with h=11.5mm, Ws=13.5mm, w=1.4mm, Ls=32.4mm, L=28mm on a FR4 substrate with ε_r= 4.3, hs=1.6mm and t=35 µm.

In order to minimize the radiation outside the human body, the antenna is placed inside a rectangular cavity with optimized dimensions (6cmx6cmx3cm) to increase the antenna directivity and to focalize the energy in the phantom. The simulation results which are depicted in Fig. 3 show that placing the antenna inside the cavity has a small influence on the resonance frequency. However, the directivity of the antenna is globally enhanced about 3 dB in the breast direction, (*e.g.* from 3.9 dBi to 6.9 dBi with and without the cavity respectively at 2.21 and 2.26 GHz).

Then, an inhomogeneity of a 5 mm length cubic shape is introduced in the breast phantom representing a malignant tumor [9-10]. This tumor was located at approximately 2 centimetres below breast skin in the glandular tissues layer which corresponds to the most commonly encountered cases. The electric properties of the tumor are set to ε_r=50 and σ=4 S/m. Figure 4(a) illustrates the back-cavity antenna applied on the malignant breast model and figure 4(b) shows the simulated return loss of the antenna when implanted on the healthy model and on the malignant breast phantom. When the tumor is introduced in the model, the resonant frequencies are down-shifted respectively of about 30 MHz and 50 MHz for the lowest and highest resonant frequencies corresponding to 3.5% and 2.2 % relative down-shifts. It should be pointed out that many simulation and optimization runs have been made to improve the sharpness of the resonance in order to increase the detection sensitivity while keeping a satisfying forward directivity and pattern radiation. The antenna presented here corresponds to a satisfying compromise over the entire range of variation in model parameters (thicknesses and permittivities of the tissue layers). This variation range in the model is intended to take into account the variability of electrical characteristics of real patients [14].

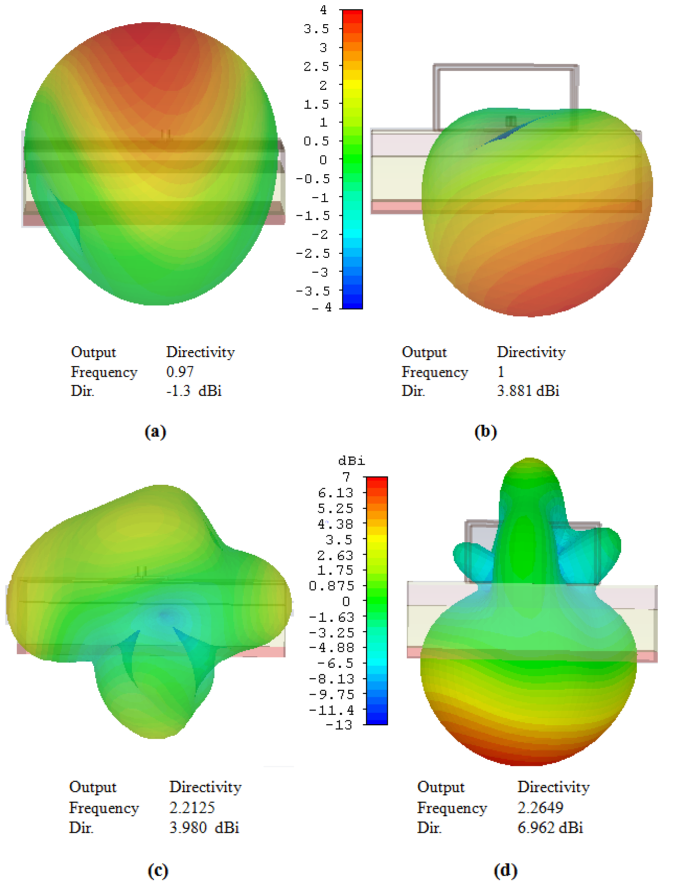
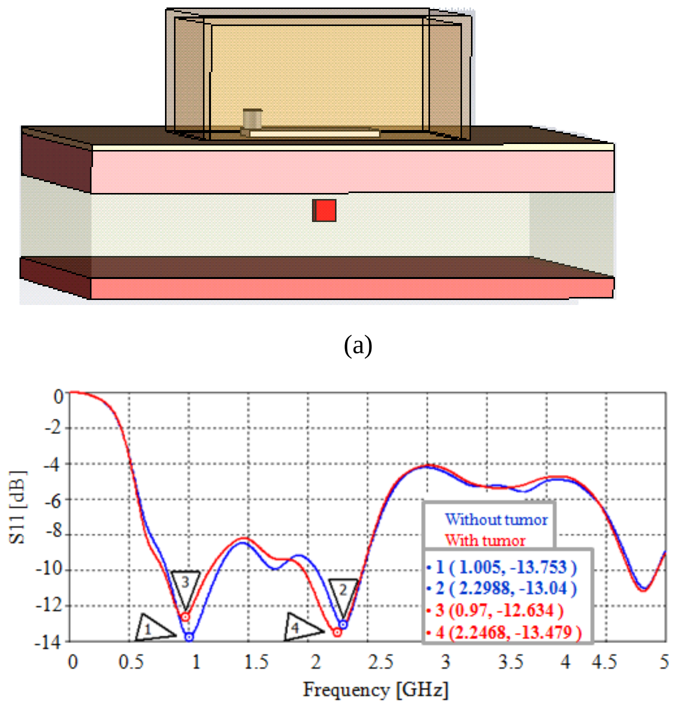


Fig. 3. Comparison of radiation patterns without (a and c) and with the back-cavity (b and d), respectively at the lowest (a and b) and highest (c and d) resonant frequencies.



(a)

(b)

Fig. 4. (a) Malignant breast model with the back-cavity HFA, (b) simulation results ($|S_{11}|_{dB}$) without and with the tumor.

IV. MEASUREMENT RESULTS

A. *Measurement protocol*

The designed antenna was manufactured (Fig. 5) and the measurement protocol was applied on two different patients aged over 65 years suffering from breast cancer at the CHRU of Brest (Centre Hospitalier Régional et Universitaire de Brest). The protocol used in our measurement is identical to that of ultrasonography usually used in medical care centers for breast cancer detection. The breast is divided into several zones or areas that look like the decomposition of a wall-clock. The measurements of S_{11} and resonant frequencies at each zone were performed using an Anritsu portable Vector Network Analyzer. Ultrasonography measurements have also been performed for both patients on the same zones of the breast to locate the lesion before our measurements. Hence, a comparison between measurements will be possible in order to validate or invalidate the feasibility of heterogeneity detection using a direct frequency shift measurement.

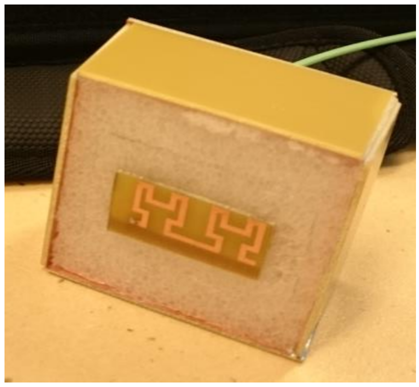


Fig. 5. Photograph of the back-cavity Hilbert-Fractal Antenna.

B. *Measurement Analysis*

- For patient 1, Fig. 6(a) illustrates the position of the measurements displayed as a clock hour around the nipple and also the tumor position localized by ultrasonography. The tumor has a width of 17.8x15.7mm and was located at 18mm below the skin at a 9h30 clock-position. Return loss for different positions of the antenna on the breast are depicted in Fig. 6(b). First of all, the overall shape of the curve is different compared to simulations results which can be explained by a rather random distribution of mammary glandular tissues not taken into account in our model. A raw and wideband analysis indicates that the measurement made over the tumor does not stand out significantly from the set of curves. A finest analysis (Fig. 6(d)) shows that the stronger shift towards the low frequencies of the high resonance frequency is observed above the tumor. The possibility of detection must however be undervalued by the relatively low frequency-shift that is obtained and by the degradation of the high-frequency resonance at 6h- and 7h-positions.

- The same analysis (Fig. 7) has been performed for patient 2. The tumor was between position 1h and 1h30 at 14.8 mm below the skin with smaller dimensions: about 10x4mm. The wideband responses (Fig. 7(b)) clearly show a global down-shift in frequency of the measurement over the tumor which is confirmed by analysis of the narrow-band curves, particularly for the upper resonant frequency (Fig. 7(d)). Once again, these results are however relative, because the measurements on healthy areas present also frequency-shift variations. Furthermore, while measuring, a significant change in return loss-response has been observed at position 2h30. Thus, a thorough investigation was performed by the radiologist using ultrasonography imaging at this area, and a 4x4mm cyst was then detected. The presence of this latter explains the significant change of the return-loss response at the higher resonance frequency of the antenna.

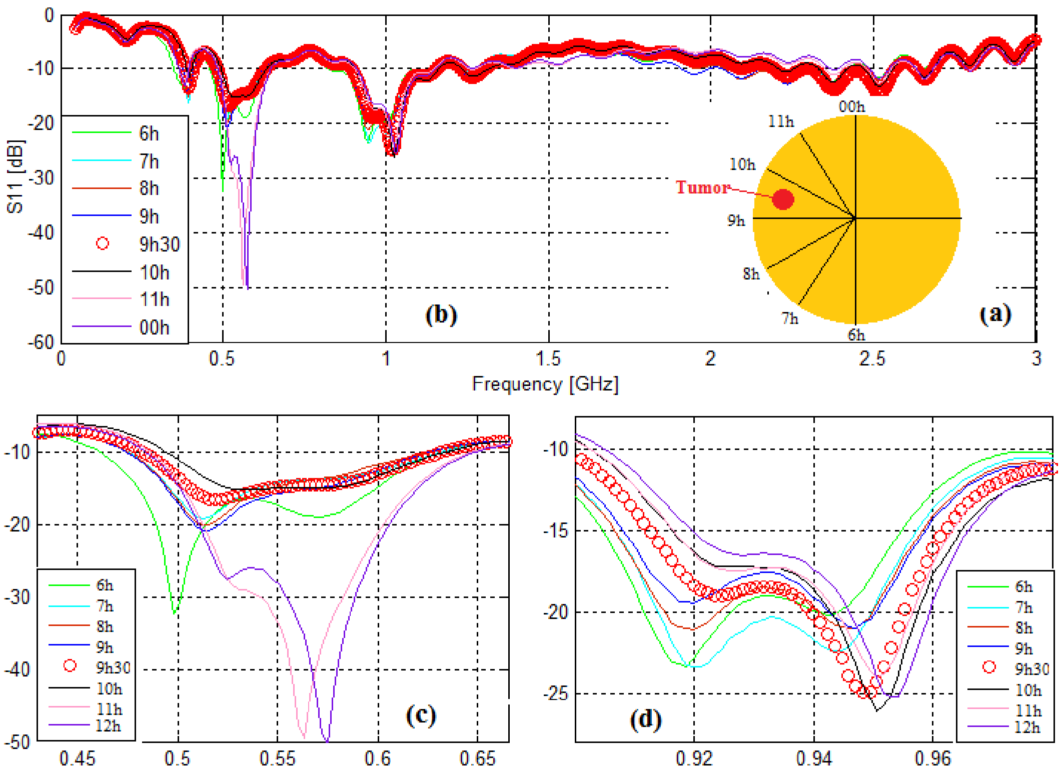


Fig. 6. Patient 1: (a) Tumor and measurement positions, (b) corresponding measured return-loss and (c) and (d) zooms on resonant frequencies.

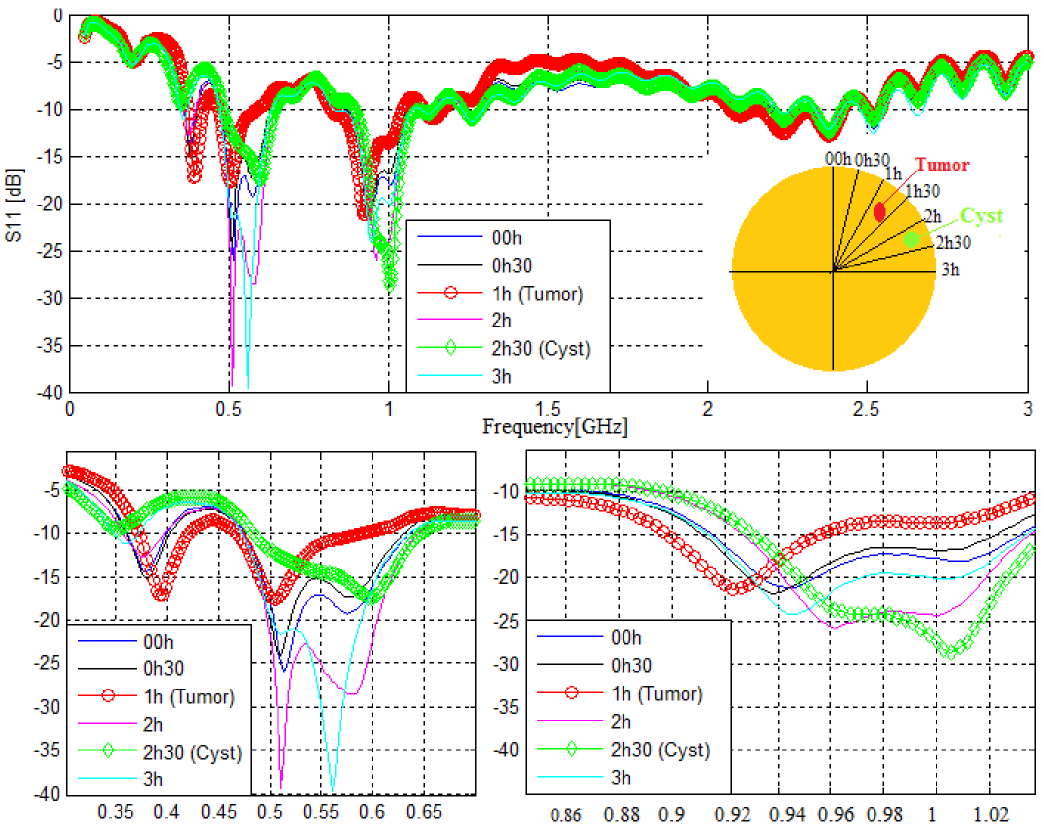


Fig. 7. Patient 2: (a) Tumor and measurement positions, (b) measured return-loss and (c)-(d) zooms on resonant frequencies.

Ex-vivo measurements were performed in order to characterize the tumors' permittivity immediately after their resections in surgery. We used a microwave coaxial probe with a tiny sensing area (depth of 3 mm) which was directly placed on the excised specimens after a calibration procedure. These measurements allow us to validate the tumor permittivity used in the proposed model. Electrical properties of *ex vivo* tissues differ from their *in vivo* counterparts; therefore, it is important to get *ex vivo* properties of excised tissues as soon as possible after the surgery. These results were performed in two different configurations: the tumor 1 was characterized by placing the probe directly in contact with the surface of the resected portion, while the tumor 2 was cut in half to allow a direct measurement on the tumor itself.

As depicted in figure 8, the relative permittivity of tumor 2 ranges between 55 and 60 in the considered frequency band, whereas tumor 1 is closer to 50 due to the presence of fat and blood. These results confirm values used in literature and also in our simulation [9-11].

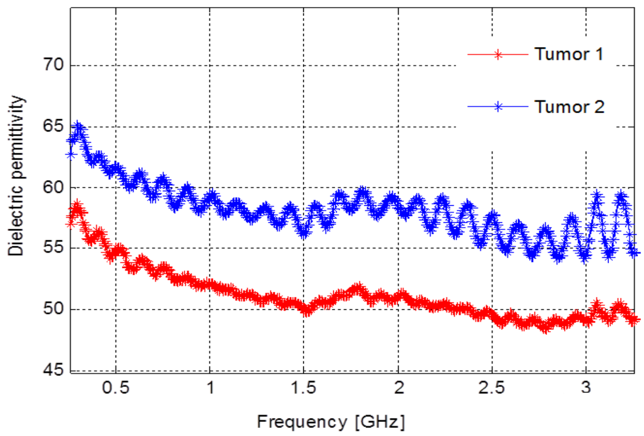


Fig. 8. Characterization of tumors' permittivity.

V. CONCLUSIONS AND FUTURE WORK

In this paper, the design of a Back-cavity HFA for microwave detection of breast tumors was presented. The simulation results show that the antenna response is affected in terms of frequency and return loss when it's implanted on the malignant model compared to the healthy one. The Measurement protocol was applied on 2 different patients diagnosed with breast cancer. Measurement results show significant differences compared to simulated ones, this feature is explained by the fact that the theoretical model do not represent precisely enough the real constitution of the breast, particularly the inhomogeneous structure of the glandular area. The first conclusion to be drawn is that the most often commonly used breast model, i.e. planar multi-layers, should be restricted to first steps of the antenna design. Moreover, the great disparity in the distribution and permittivity values of the glandular system [14] from a woman to another greatly limits the relevance of such a direct frequency technique for breast tumor detection. Consequently, in order to design a microwave low cost and simple tumor detector that could be handled like a "simple stethoscope", our further work focuses on the design of a compact UWB directive antenna to detect and especially to localize the tumor using ultra-short pulses using time-domain techniques.

ACKNOWLEDGMENTS

The authors would like to thank the patients for their consent for doing the measurements, also Mr. Alexis Chevalier from the lab-STICC UBO for his help in the tissue permittivity measurements. The mobility part of this work was funded by UBO (University of Brest).

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