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A Robust Multi-Band Sierpinski Gasket Monopole for Microwave Breast Cancer Imaging

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***Abstract*—Thanks to the intrinsic self-similarity, fractal antennas are characterized by multiple resonances, a feature that could be exploited in microwave imaging (MWI) for breast cancer to gather more information about the nature and position of the tumor. A Sierpinski gasket monopole antenna is presented in this paper, showing three operating bandwidths as well as high robustness to the presence of a numerical mammary phantom.**

Keywords—fractal antenna, breast cancer, microwave imaging, SAR

I. INTRODUCTION

One of the world's leading causes of death among women is breast cancer [1]. Diagnostic techniques allow a preventive identification of the pathology, effectively reducing mortality from malignancies. The most prominent ones include x-ray mammography, Magnetic Resonance Imaging (MRI), ultrasound, and Computed Tomography (CT) [2]. X-ray mammography is certainly the most used for preventive screening but requires breast compression, which is uncomfortable for the patient, involves ionizing radiation and often lacks accuracy [2]. MRI is safer and more comfortable but is a lengthy and high-cost procedure, thus not recommended for early detection of the tumor nor for monitoring purposes [2]. Finally, CT employs a higher dose of ionizing radiation w.r.t. the mammography and does not always offer a fair discrimination among soft tissues [3].

For these reasons, Microwave Imaging (MWI) is an appealing candidate as a screening tool for early breast tumor detection and monitoring, being a safe (non-ionizing radiation), non-invasive and low-cost alternative to standard procedures [1]. This technique is based on the dielectric contrast between the tumor and the normal breast tissue. As such, suitable radiators have to be employed in order to transmit a radiofrequency (RF) and/or microwave (MW) signal and measure the scattered field. In this context, the antenna characteristics, such as size, operating frequency and bandwidth, play an important role, as well as the number of antennas employed that directly affect the spatial sampling density [4]. However, to properly solve the ill-posed inverse scattering problem, also the frequency sampling density, namely the number of frequencies used for the acquisition, is of paramount importance. Therefore, antennas with multi-band features fit this role extremely well.

Multi-band behavior can be found in a particular category of antennas known as fractal antennas, which exploits the self-similarity to obtain multiple bandwidths and to reduce the overall size of the antenna [5]. In the open literature, there are only few examples of fractal antennas used for microwave breast tumor imaging [6]–[10] and none of these examples propose a layout based on the Sierpinski gasket.

In this paper, a robust, multi-band Sierpinski gasket monopole for breast cancer imaging is proposed. The antenna is characterized by three useful bandwidths at 1.737 GHz (9.15% BW), 3.53 GHz (25.2% BW), and 6.9 GHz (20.3% BW) and shows a high robustness with respect to a numerical breast phantom. The Specific Absorption Rate (SAR) is also analyzed, showing values below the European regulated threshold levels.

II. ANTENNA DESIGN

The proposed antenna is a fractal monopole based on the Sierpinski gasket with coaxial feeding and orthogonally placed over a groundplane (120 mm x 120 mm). The monopole is printed on a 1-mm thick FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.002$). Both monopole and groundplane are made of copper and the thickness of the metallization is equal to 0.035 mm. The height of the main triangle of the Sierpinski gasket is equal to 88.9 mm. The Sierpinski gasket is based on the iteration process applied to the main equilateral triangle, in which at each step a central inverted triangle is subtracted from the original one. Every subtracted triangle is half the size of the starting one and the iteration can be repeated an infinite number of times. Thanks to its self-similarity the antenna can show multiple resonances while retaining a compact size. In the presented case the iteration has been stopped at the second step, since there are no additional benefits for further steps. The design steps of the proposed monopole are reported in Fig. 1. Following the first iteration, the first subtracted triangle has a height equal to 44.45 mm, whereas the second one has a height of 22.25 mm. It is worth noting that the triangle cuts on the main antenna are not exactly half of the original triangle, but slightly shorter (about 0.1 mm). This expedient allows the current to flow toward the upper portions of the antenna itself, otherwise only the small bottom triangle could resonate.

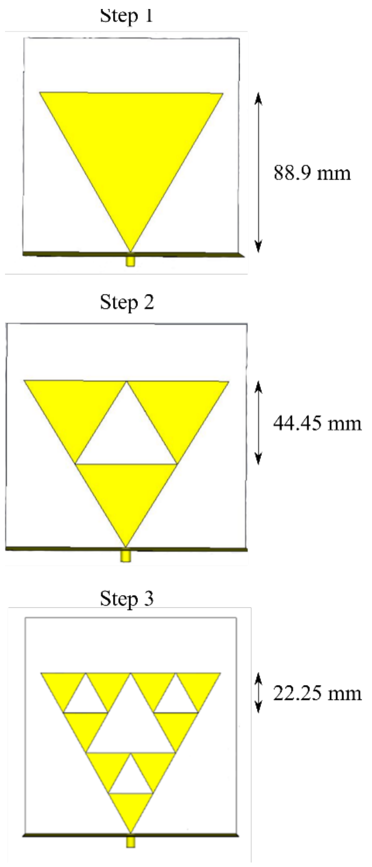


Fig. 1. Design steps of the proposed Sierpinski monopole antenna.

III. SIMULATION ENVIRONMENT AND RESULTS

All the simulation herein reported are carried out using CST Studio Suite 2019 (3Ds, Simulia, DE). The frequency response of the final layout (2nd step of the Sierpinski iteration) in free space is reported in Fig. 2.

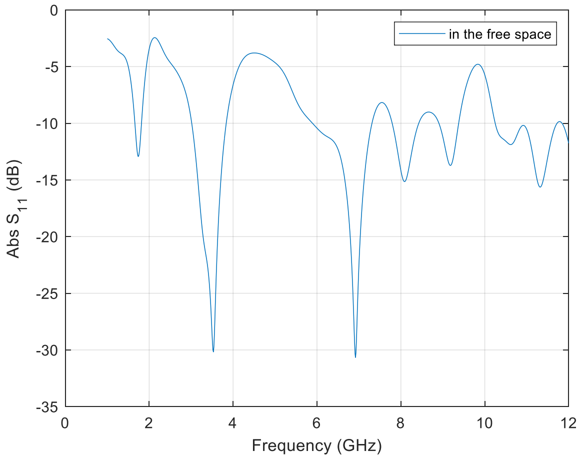


Fig. 2. S_{11} of the proposed antenna deployed in free space.

From the presented result, three operating frequencies are visible, each one referable to one iteration:

- i) From iteration 0, the main triangle resonates at 1.737 GHz with a fractional bandwidth of 9.15% (159 MHz).
- ii) From iteration 1, the triangle with half the size of the main one resonates at 3.53 GHz with a fractional bandwidth of 25.2% (590 MHz).
- iii) Finally, from iteration 2, the triangle with half the size of the second triangle (or a quarter of the size of the main one), resonates at 6.9 GHz with a fractional bandwidth of 20.3% (890 MHz).

The antenna shows three operating frequencies that can be exploited to gather more information about the nature and position of the tumor.

In order to study the interaction between the antenna and the human body, a numerical breast phantom had to be introduced in the simulation environment. The mammary phantom has been built considering a hemisphere with radius r = 100 mm, located at a distance d = 50 mm from the fractal antenna. The hemisphere is composed of a superficial skin layer with thickness 2 mm and an internal hemispheric layer of fatty tissue. Such phantom lies on top of a 5-mm thick layer of muscle tissue mimicking the pectoral muscle. To account for the neoplastic scenario, two spherical tumors have been inserted within the fatty tissue of the breast phantom, one with radius equal to r_1 = 10 mm and the other one with radius equal to r_2 = 5 mm. The complex dielectric constant for the biological tissues has been taken from the IT'IS database [11] and it is reported in Tab. I.

TABLE I. COMPLEX DIELECTRIC PARAMETERS OF THE SIMULATED BIOLOGICAL TISSUES.

Tissue	ε_r (f = 1.737 GHz)	σ (f = 1.737 GHz)	ε_r (f = 3.53 GHz)	σ (f = 3.53 GHz)	ε_r (f = 6.9 GHz)	σ (f = 6.9 GHz)
Skin	39	1.16 S/m	37	2.04 S/m	34.2	4.72 S/m
Fat	5.28	0.09 S/m	4.93	0.22 S/m	4.31	0.51 S/m
Muscle	53.6	1.31 S/m	51.4	2.58 S/m	47	6.33 S/m
Tumor	63	3.80 S/m	60	6.00 S/m	56	9.00 S/m

The S_{11} of the antenna in proximity to the numerical phantom breast is reported in Fig. 3 and it is compared with the free space response.

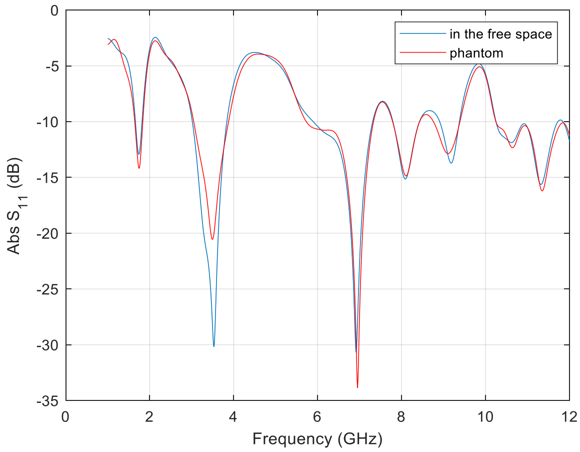
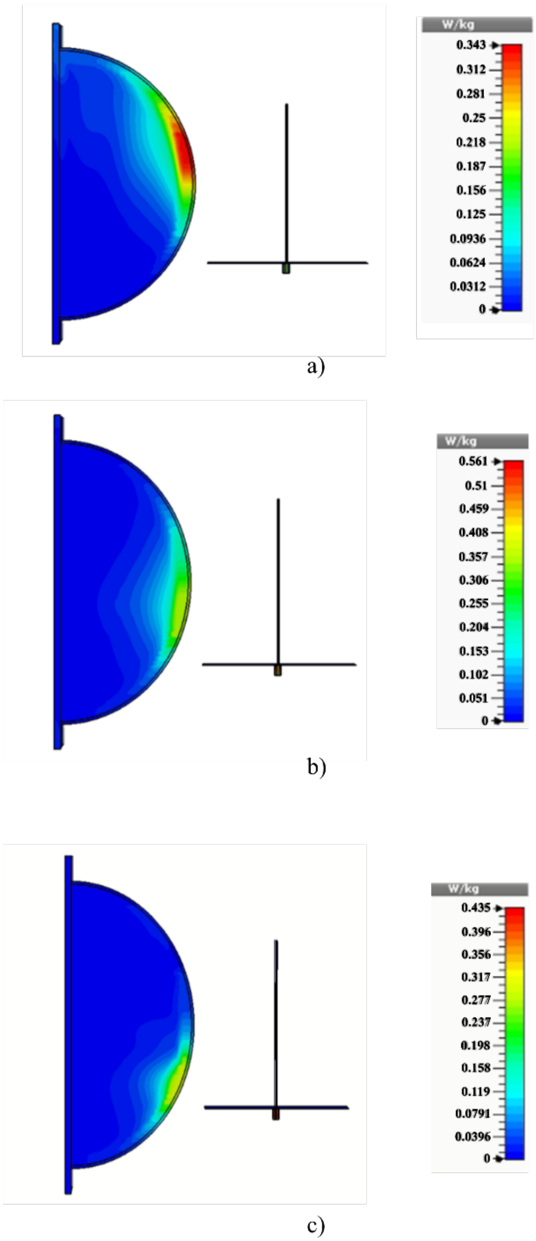


Fig. 3. Comparison between the S_{11} of the proposed antenna in free space and in proximity to the numerical breast phantom.

As shown in the image, the presence of the mammary phantom has little effect on the antenna frequency response, which can be considered, therefore, robust. The Specific Absorption Rate (SAR), an index of the amount of electromagnetic energy absorbed by the human body, has also been analyzed. The results are reported in Fig. 4.



a)

b)

c)

Fig. 4. SAR values considering an antenna input power of 0.5 W for the three frequencies of interest: a) 1.737 GHz, b) 3.53 GHz, c) 6.9 GHz.

Fig. 4 reports the simulated levels of SAR considering an input power at the antenna of 0.5 Watts. The threshold levels according to the European Union regulation must not exceed 2 W/Kg. In all three cases, the level of SAR is below the threshold.

IV. CONCLUSION

A Sierpinski gasket monopole antenna for breast tumor imaging is presented in this paper. The self-similarity of the fractal antenna allows to take advantage of three frequency bandwidths, at 1.737, 3.53, and 6.9 GHz. The antenna is first analyzed in free space, then simulated in proximity to a numerical breast phantom, showing high robustness with respect to lossy and inhomogeneous large objects such as biological tissues. To ensure that the EU threshold levels for electromagnetic absorption are complied also a SAR analysis is carried out.

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