A Microwave Breast Imaging System using Elliptical Uniplanar Antennas in a Circular-Array Setup

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***Abstract*— Microwave tomography has attracted significant research interest as it offers a non-ionizing diagnostic technique for breast cancer. A microwave breast imaging (MBI) system comprises an array of antennas, which illuminates the tissue and measures the scattered energy in order to spatially allocate the dielectric permittivity and conductivity of the tissue. The radiating elements of a MBI system should be compact and wideband. This paper describes an elliptical uniplanar antenna 40 mm x 50 mm in size that operates in the 1.53-3.33 GHz range when placed against a breast phantom. The antenna is used as the radiating element in a circular-array setup around a hemispherical phantom. Simulated and measured data from the proposed array are presented, which show satisfying agreement and system performance.**

Keywords—microwave breast imaging, mcrowave tomography, elliptical uniplanar antenna, virtual antenna array

I. Introduction

Microwave tomography is an emerging modality for breast cancer detection that has attracted significant research interest the last two decades. In comparison to X-ray imaging, microwave breast imaging offers a non-ionizing diagnostic tool for detecting malignancies surrounded by healthy tissue and benign tumors. The frequent use of mammography, especially on young patients or women without any symptoms as part of prevention examination, has been questioned. Another serious disadvantage is a high rate of false positive and false negative results [1].

Microwave tomography uses an array of transmitting/receiving antennas that radiate the breast and collect the scattered energy. By using the appropriate algorithms that solve the inverse EM scattering problem, microwave imaging calculates the spatial dielectric profile of the tissue [2]–[4]. Healthy breast tissue, benign and malignant cancerous tissues present different dielectric properties in the microwave regime [5], [6]. Thus, microwave tomography promises an effective imaging technique that offers measurable contrast between healthy tissue and tumor.

The operating bandwidth of a microwave imaging system has been extensively discussed [7]–[9]. Lower frequencies (around 1 GHz) present deep penetration and allow a rough scanning of the entire volume of the tissue. However, the low operating frequency of the system is limited by the size of its radiating elements. On the other hand, higher frequencies improve the imaging resolution, but they are highly attenuated inside the breast. Practically, frequencies beyond 4 GHz are not detectable, since the conductivity of human tissue significantly attenuates these signals [8].

As a result, the radiating elements of microwave breast imaging systems have to be compact, wideband with a low cut-off frequency. Also, their topology should be geometrically simple in order to be easily modeled by inverse scattering algorithms. Monopoles are attractive candidates, because of the simplicity of their architectures [7] and Vivaldi antennas offer an ultra-wide operating bandwidth [10], [11]. Alternative topologies have also been proposed [12], [13].

This paper describes a newly developed elliptical uniplanar antenna that comprises an elliptical patch and a surrounding coplanar ground plane [14]. Under free-space conditions the fractional bandwidth is 53%, which means that the antenna can be considered as ultra-wideband. When the antenna is placed against a breast phantom, its operating bandwidth extends from 1.53 GHz to 3.33 GHz (fractional bandwidth 74%). The antenna is compact (40 mm x 50 mm) and it presents a relatively simple architecture. An array setup of six elliptical antennas radiating into a breast phantom is also examined. In the following sections, the performance of the antenna is presented through simulated and measured data which are demonstrated in detail.

II. Uniplanar Elliptical Antenna

The antenna is a rectangular uniplanar antenna measuring 40 mm x 50 mm and it comprises an elliptical patch with a major axis of 26 mm and minor axis of 13 mm. The transmission line is smoothly flared. The ground plane

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surrounds the elliptical monopole forming a "window" in order to extend the operating bandwidth to lower frequencies by extending the path traversed by the ground currents, since both element and ground currents radiate. The geometrical configuration of the antenna is shown in Fig. 1. The substrate exhibits a dielectric permittivity ε_r = 10.2 and a loss tangent tanδ = 0.003 (Rogers RO3210) and it is 1.27 mm thick.

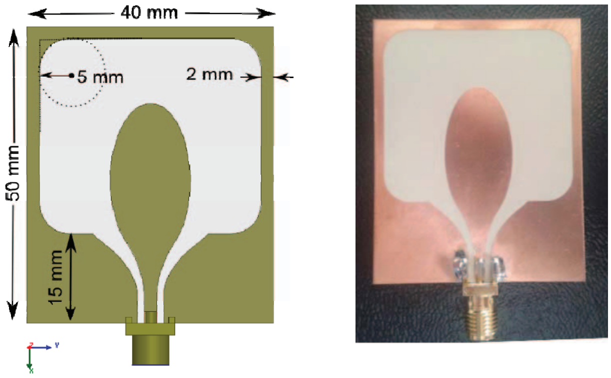

Fig. 1. Uniplanar elliptical antenna.

The antenna was designed and simulated in ANSYS HFSS. The port impedance was set to Z_{port} = 50 Ω. The reflection coefficient of the antenna was also measured under free-space (FS) conditions using a VNA, but without using a balun transformer. Measurements and simulation results are shown in Fig. 2. Simulated data show a bandwidth of 1.3 GHz (1.8-3.1GHz) at a reflection level of -10 dB, and therefore, a fractional bandwidth of 53%. According to measured results, the operating bandwidth of the antenna spreads from 1.50 GHz to 3.05 GHz at a reflection level of -6 dB.

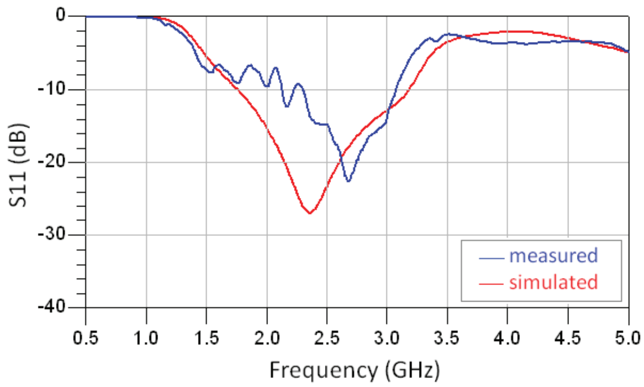

Fig. 2. Measured and simulation results of the broadband magnitude of the reflection coefficient at the input to the uniplanar elliptical antenna under free space conditions.

III. Circular Array Setup

The performance of the antenna was tested in an array setup around a hemispherical phantom with 8 cm radius. The recipe that was used for the breast phantom consisted of distilled water (47%), sugar (47%) and gelatin (6%) [15]. The values of the dielectric properties of the phantom in the operating bandwidth of the antenna are ε_r = 20 and σ = 1 S/m.

The elliptical uniplanar antenna is basically a monopole, and thus its radiation pattern is omnidirectional around the major axis. The array is comprised of six elements that are placed vertically against the surface of the phantom and parallel to its circumference (Fig. 3). The angular distance between adjacent elements is 60°.

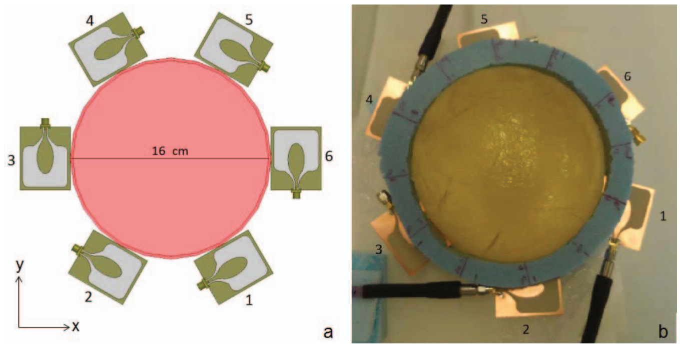

Fig. 3. a. The design of the circular array setup consisting of six ellptical uniplanar antennas around breast hantom. b. The respective experimental circular setup.

Numerical analysis and experimental measurements were performed. Fig. 3.b shows the experimental setup of the array. A ring constructed by extruded polystyrene foam (styrofoam) with 6 parallel slots was used to hold the antennas at the proper position. A VNA with four ports was used. This array setup presents circular symmetry and thus, only antennas #1, #2, #3 and #4 were active, while antennas #5 and #6 were terminated with coaxial 50 Ω ohmic loads. However, no balun transformer was used during measurements.

A. Numerical Analysis

The array setup was simulated and the scattering parameters were calculated in ANSYS HFSS at the frequency range 0.8-3.5 GHz (Fig. 4). As the array setup presents circular symmetry, only the effect of antennas #1 to #4 is shown. Each element presents a reflection coefficient that is lower than -9.8 dB at a frequency range from 1.529 GHz to 3.338 GHz. Adjacent elements present the strongest mutual coupling which is maximum (-40 dB) at 2.02 GHz.

Fig. 5 shows the electric field distribution inside the phantom on the xz-plane when antenna #6 is active at 2.00 GHz. The color map was clamped at a maximum field strength of 20 V/m. The penetration depth, considering that no matching medium is used, is approx. 4 cm.

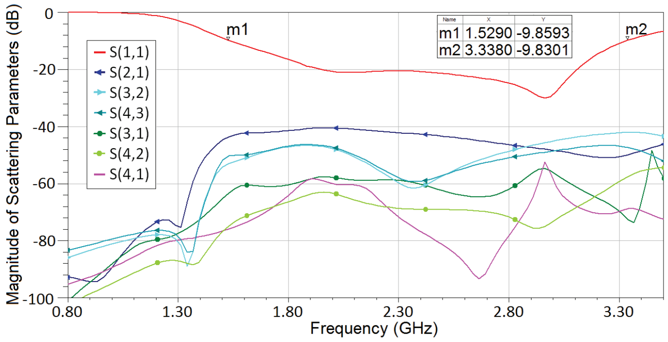

Fig. 4. Simulation results of the magnitude of the scattering parameters of the elliptical antenna array around hemispherical phantom.

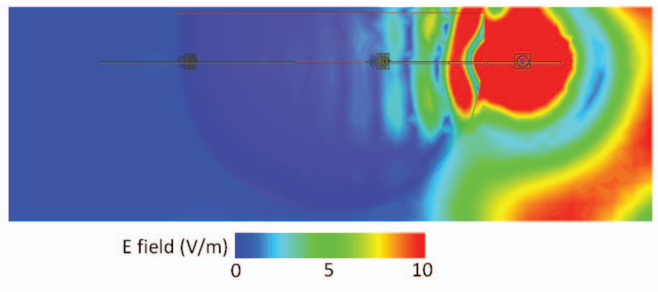

Fig. 5. The E-field distribution on the xz-plane inside the phantom when the antenna #6 is active at 2.00 GHz.

B. *Experimental Results*

The magnitude of scattering parameters of the antenna array is shown in Fig. 6 and Fig. 7. As expected, mutual coupling is stronger between adjacent elements and scattering parameter, S_{21}, takes a maximum value of -19.5 dB at 1.454 GHz. Simulation results (Fig. 4) had indicated, however, that mutual coupling peaks at -40 dB. This difference between numerical analysis and measurements is explained by the fact that during measurements no balun transformer was used: stray unbalanced currents on the outer sheath of the coaxial cables, which radiate, run tangential to the styrofoam ring. As a result, the radiating elements of the array are electromagnetically "closer".

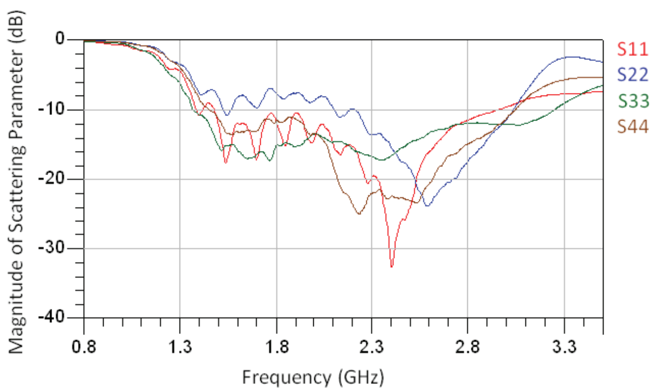

Fig. 6. Measured reflection coefficients of antennas #1, #2, #3 and #4.

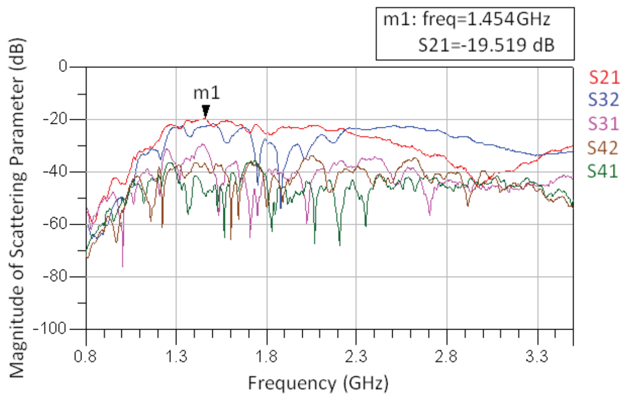

Fig. 7. Measured transmission coefficients of antennas #1, #2, #3 and #4.

IV. CONCLUSIONS

This paper described an elliptical uniplanar antenna as a radiating element for a microwave breast imaging system. The antenna comprises an elliptical patch and a ground plane forming a "window" around it. This design aimed to artificially increase the size of the antenna and extend the operating bandwidth to lower frequencies. Meanwhile, the smooth flaring of the elliptical patch and the transmission line perturb the currents in a way that higher modes are excited. The operating bandwidth is 1.8 GHz and the low cut-off frequency at 1.53 GHz, when the antenna is placed against a breast phantom.

The scattering parameters of the array were measured without using a balun transformer. However, the proposed circular setup presents low mutual coupling, as maximum transmission coefficient of adjacent elements is -19.5 dB.

The presented measurements were performed in order to evaluate the performance of the proposed antenna. In later stages of this ongoing research, the measurements will be repeated using the appropriate balun transformers before the input of the antenna and a matching liquid in order to enhance the energy coupling with the tissue. The measured scattering parameters will be used by an appropriate algorithm that solves the inverse scattering EM problem, in order to reconstruct the tissue image.

ACKNOWLEDGMENT

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: "MiSCAN" - Microwave Imaging for Screening of CANcer: A prototype system for diagnosis of superficial and deep tumors.

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