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Combining Reflector Focused and Phased Array Beamforming for Microwave Diagnosis and Therapy

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Abstract— **In this paper we continue our recently reported work on the exploitation of the focusing properties of a conductive ellipsoidal reflector in conjunction with directive phased antenna configurations in order to achieve diagnosis and therapy at the microwave frequency regime. Both aforementioned modules are parts of a hybrid microwave radiometry and hyperthermia system comprising a symmetrical axis ellipsoidal conductive wall cavity which ensures the necessary beamforming and focusing on the body/brain areas of interest. The proposed system operates in an entirely non-invasive contactless manner providing temperature and/or conductivity variations monitoring while it is also designed to provide hyperthermia treatment. Recently, the effect of the use of patch antennas as receiving or emitting elements on the system's focusing properties and specifically the use of two-element phased array setups to achieve scanning of the areas under measurement was investigated. In the present paper, four element antenna setups are used and extensive simulations to compute the electric field distributions inside the whole ellipsoidal reflector and inside two types of human head models were carried out. The results show that clear focusing (creation of "hot spots") inside the head models is achieved at 1GHz. In the case of the four element antennas, the "hot spot" performs a linear scan around the brain area of interest while the phase values of the four antenna elements significantly affect the way the scanning inside the head model is achieved. The proposed setups enhance and increase the dimensions and scanning of the focusing area toward the acquisition of tomography images without the need of subject movement.**

Keywords— Microwave Radiometry, Phased Array, Ellipsoidal Cavity, Electronic Scanning

I. INTRODUCTION

A Microwave Radiometry Imaging System (MiRaIS) has been developed and experimentally used the past 7,5 years for passive brain diagnostic applications [1]-[8]. The operating principle of the system is based on the use of an ellipsoidal conductive wall cavity to effectively guide and converge radiation on the brain areas of interest. MiRaIS has been used in various experiments with the aim to validate its future potential clinical value [1]-[7]. The results show that the system is able to provide real-time temperature and/or conductivity variation measurements in water phantoms and animals [1]-[6]. Human experiments indicated the potential value of using focused microwave radiometry to identify brain activations possibly mediated in operations induced by particular psychophysiological tasks [1], [2]. Finally, the experimental use of the MiRaIS has also provided preliminary results regarding the incidence of possible temperature and/or conductivity changes as a result of mobile telephony usage [9].

During the aforementioned research, various approaches to optimize the system's focusing properties and performance, have been followed both theoretically and experimentally spanning from receiver performance improvement (use of sensitive multiband receivers e.g. [4]), to the use of matching materials to improve beamforming (e.g. [5]). The system was upgraded to a hybrid one performing both diagnosis and treatment [6], [7] In parallel, near field configurations using phased array systems towards the development of more portable solutions were also developed [10], [11]. The use of matching dielectric or metameterial layers surrounding the human head combined with multiband sensitive radiometers have significantly improved the detection depth and spatial resolution of all systems [5], [7], [12], [13].

Since, the initial scope of research was the development of a tomography modality, a motor based mechanism for three-dimensional raster scanning that provides the required tomography images was used [1]-[8]. All the experiments performed to date comprised the use of dipole or discone antennas, i.e. omnidirectional antennas placed on one ellipsoidal focus point while the area of phantom or subject head to be monitored was placed at the other focal area of the ellipsoidal reflector. Recently, we theoretically investigated the effect of the use of patch antennas as receiving/emitting antennas on the system's focusing properties and specifically the use of phased array setups to achieve scanning of the areas under measurement in a simulation study [14]. Since promising results were yielded, in this paper, we focus on studying the performance of four-element patch phased antenna arrays in terms of focusing and scanning performance improvement.

II. MATERIALS AND METHODS

A. System Description

The system (Fig. 1) comprises two modules; one for monitoring with microwave radiometry and another for treatment with microwave hyperthermia. The system consists of an axis-symmetric ellipsoidal cavity with an opening aperture to host the human head that is monitored or receives the focused brain hyperthermia [6], [7]. The cavity has 1.25m length of large axis and 1.20m length of small axis. All system modules and details are depicted in Fig.1.

The ellipsoidal conductive wall cavity provides the necessary focusing and beamforming of the electromagnetic energy on the area of interest. The geometrical properties of the ellipse indicate that rays originating from one focal point will merge on the other focal point. Exploiting this geometrical optics attribute, when the system is used for microwave radiometry the medium of interest is placed at one focal point, whereas a receiving antenna is placed at the other one. In this way, the chaotic electromagnetic energy emitted by the medium of interest is received by the antenna and driven to a radiometer for detection (Fig. 1). In the case of hyperthermia, the area of interest under treatment is placed on one focal point, irradiated by the emitting antenna positioned at the other ellipsoidal focus.

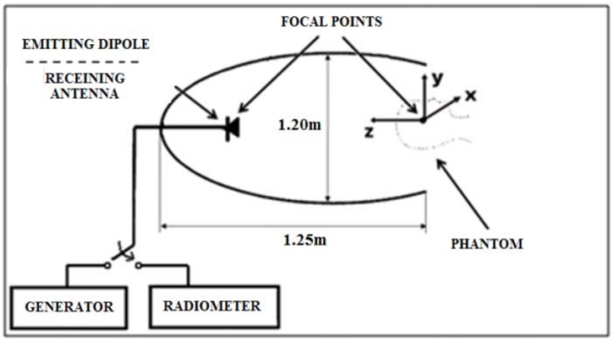


Figure 1. The Hybrid MiRaIS for monitoring and treatment

In the simulations presented herein the reciprocal problem is solved in order to reduce the computational cost imposed by the solution of the initial "forward" problem. Hence, instead of placing the source in the head model, the response of the spherical head model, placed on one focal point of an ellipsoidal cavity, to the excitation generated by an antenna, positioned on the other focus, is calculated. When a region of the head is placed at the focal point the energy emitted by the antenna converges on this area but presenting a variety of penetration depths, spatial resolution and spatial sensitivity that are frequency depended as shown in previous theoretical and experimental studies [1]-[8], [13].

B. Antenna and Head Model Setups

In this paper, the analysis of the electromagnetic problem is approached numerically using commercial FEM solver (High Frequency Structure Simulator, HFSS, Ansoft Corporation). The aim is to investigate the effect of the use of four element patch antenna arrays as receiving/emitting antennas on the system's focusing properties.

The simulations presented in Section III have been performed using a four element microstrip patch emitting antenna placed at the ellipsoidal focus with each antenna element forming an angle of 45° with the horizontal axis (Fig.2). The latter configuration has been used in the simulations as a phased array system and the system's focusing properties have been investigated for various phase difference values Δφ. The abovementioned placement angles of the antennas with respect to the horizontal axis were chosen after performing several simulations and observing the field convergence at the ellipsoidal's focal area. The patch antennas have resonant frequency at 1GHz with dimensions 187 mm x 160 mm (substrate), 110 mm x 98 mm (patch) on dielectric Rogers RT/duroid 5880, with dielectric constant εr = 2.2 and thickness of 1.5748 mm. A coaxial feed has been used and the feed is done at d = 19.5 mm from the antenna patch center along the y axis.

Additionally, the analysis is performed for two types of head models; a spherical head model and a more detailed anatomic one (SAM -Standard Anthropomorphic Mannequin) whose shape and dimension are specified in a CAD (computer aided design) file included with EN 50361-2001 and IEEE 1528-2003. The spherical model is double –layered comprising two kinds of tissue, skull and brain gray matter, whereas the SAM model comprises only the brain gray matter. Electrical characterization of the tissues in both models has been based on literature data at 1GHz [15]. Both head models are surrounded by a matching lossless dielectric material of εr= 6.15 and 1cm thickness which, as previously shown, significantly improves the system focusing properties minimizing the electromagnetic wave scattering due to the more stepped change of the refraction index on the head–air interface [4], [5].

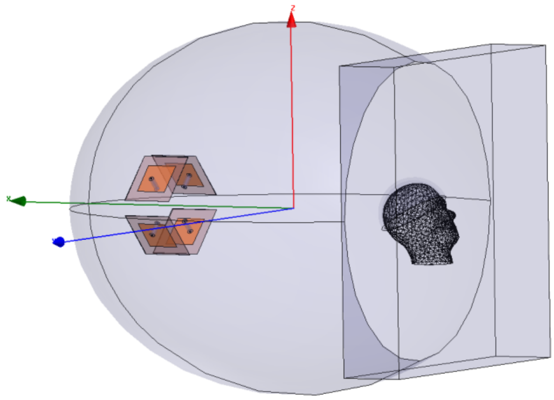


Figure 2. System configuration where the ellipsoidal reflector, the four-element patch array and the SAM head model are depicted

III. SIMULATION RESULTS

In order to use a diagnostic and therapeutic device such as the proposed one, it is of great importance to ensure imaging or irradiation of any arbitrary area inside the human head, placed on the ellipsoid's focal point where the maximum peak of radiation is achieved. Toward this goal, the current research explores the use of microstrip patch antennas in four element setups placed on one focus whereas the geometrical center of the head models are placed at the other ellipsoidal focus point. All field distributions are depicted on transversal plane cuts at the focal plane region where global maximum values occur (XZ plane). The purple dots appearing in the head models show the position of the ellipsoidal focus. This way, comparison of the positions and dimensions of the created "hot spots" (areas of energy convergence) inside the head models can be performed with respect to the geometrical focus of the reflector. All simulations were carried out 1GHz.

A. *Spherical Head Mode*

Simulations combining the four-element patch phased emitting antenna with the inherent geometrical optics-based focusing properties of the ellipsoidal cavity, were carried out. The electric field distribution inside the ellipsoidal in the case of a spherical head model with dielectric matching layer is depicted in Fig. 3. A magnification of the head model, with and without the use of the matching layer, where clear focusing of the energy is achieved can be observed in Fig. 4. The radius of the focusing area is approximately 8mm and is achieved exactly around the head model center, which is located at the ellipsoidal's focal point (Fig. 4).

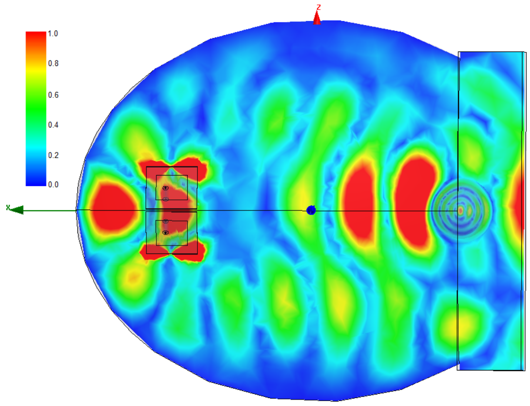


Figure 3. Field distribution inside the cavity and the spherical head model with dielectric surrounding matching material operating at 1GHz.

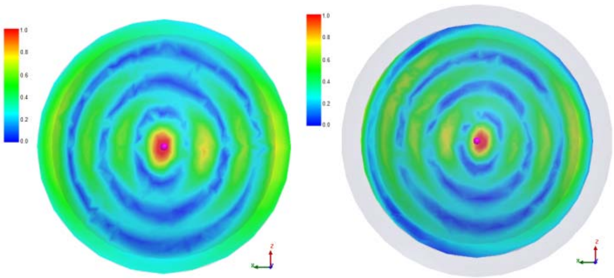


Figure 4. Field distribution inside the spherical head model with and without dielectric matching layer. The head model is centered at the focal point of the ellipsoidal.

The values of the phases of the four patch antennas are (0°, 30°, 0°, 30°), with the two top antennas having 0° phase and the two bottom Δφ=30° each. It is evident that a clear focusing area is achieved inside the head model, which moves along the horizontal (x) axis performing scanning, starting at a distance of 10mm on the left side of the focal point and finishing 10mm on the right side (Fig. 4). For various values of Δφ for the four elements similar linear scanning is achieved covering an area of the same volume displaced several centimeters in the x axis. A characteristic example is shown in Fig. 5 where the four elements have phase values (0°, 45°, 90°, 135°). It is observed that the hot spot is now formed 15mm away from the focal point in the x axis.

For greater phase differences two hot spots are created in different spatial and temporal regions, attribute which is not suitable for the application under investigation.

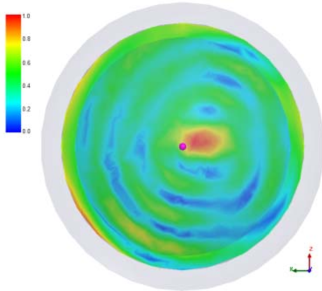


Figure 5. Field distribution inside the spherical head model with dielectric surrounding matching material operating at 1GHz with antenna phase values (0°, 45°, 90°, 135°).

B. *Anatomic Head Model*

The same simulations with the four-element phased antenna were carried out with the use of the SAM head model. The phase values for the four elements were again (0°, 30°, 0°, 30°). The case without the matching layer is depicted in Fig. 7. One can notice a primary hot spot near the focal point but also secondary ones in the areas of the nose, eyes and forehead. The primary hot spot scans a region starting 15mm above the focal point and finishing 5mm below along the z axis, crossing the focal point itself, covering an area of approximately $4cm^3$.

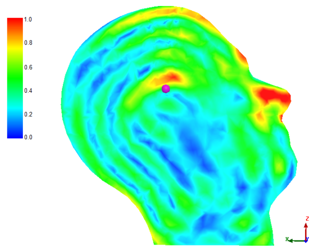
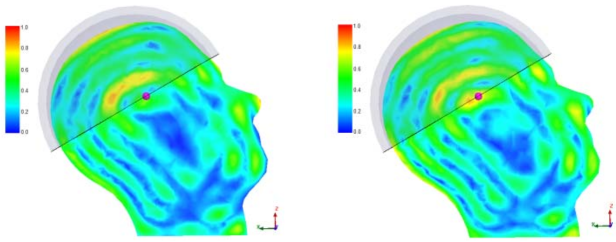


Figure 7. Field distribution inside the SAM head model without surrounding dielectric matching layer. The SAM model is centered at the focal point of the ellipsoidal.



a b

Figure 8. Field distribution inside the SAM head model with surrounding dielectric matching layer. Start (a) and end (b) of the scanning area.

When the dielectric matching layer is added, the secondary hot spots are diminished, leaving only one larger focus area around the focal point (Fig. 8). In this case the hot spot scans a region starting 15mm away the focal point in the z axis and finishing exactly at the focal point (Figure 8a,b respectively).

The phase difference of the four microstrip antennas significantly affects the way the scanning inside the head model is achieved. As the phase difference between the elements increases above 45° the electric field magnitude inside the model attenuates and finally no clear hot spot is formed. Also, the use of the dielectric matching layer prevents the creation of supereficial brain areas of high of electric field values, as was observed in [14].

IV. Discussion And Conclusion

In the present paper, we investigated the effect of the use of four-element patch antennas as receiving/emitting antennas on the focusing properties of a hybrid microwave system. In order to use a diagnostic and therapeutic device such as the proposed one, it is of great importance to have the ability to image or irradiate any arbitrary area inside the human head, placed on the ellipsoid's focal point where the maximum peak of radiation is achieved. Therefore, toward this goal, the current research explores the use of microstrip patch antennas in four element setups placed on one focus whereas the geometrical center of the head models are placed at the other ellipsoidal focus point. Two head models surrounded by lossless matching dielectric materials are used in the present simulation study; spherical and anatomic.

In all cases clear focusing inside the head models is achieved which interestingly moves performing a linear scan of several millimeters, including in all cases the focal point where the models' center is placed and scanning a volume area of approximately 4-5cm^3. The use of dielectric matcing layer diminishes the creation of secondary focal points inside the SAM model leaving only one desirable focusing region. The phase difference of the four microstrip antennas significantly affects the way the scanning inside the head model is achieved and thus with the appropriate selection of phase difference the scanning area may be successfully manipulated. This way scanning of the area of interest can be performed with significantly faster scans combining phased array induced scans in conjunction with appropriate subject movement. The present results improve previous findings [14] using two element patch phased arrays in respective simulations regarding both focusing and scanning properties.

More simulation scenarios will be investigated following various combinations of phased antenna array types and operation frequencies in order to manipulate the position and the dimensions of the energy focusing area inside the human head. Phased array antennas with multiband, increased number of elements of different patch geometries will be used in order to enhance and increase the dimensions and scanning of the focusing area toward the faster acquisition of tomography images.

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