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Passive Monitoring using a Combination of Focused and Phased Array Radiometry: a Simulation Study

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Abstract— **Aim of this simulation study is to use the focusing properties of a conductive ellipsoidal reflector in conjunction with directive phased microwave antenna configurations in order to achieve brain passive monitoring with microwave radiometry. One of the main modules of the proposed setup which ensures the necessary beamforming and focusing on the body and brain areas of interest is a symmetrical axis ellipsoidal conductive wall cavity. The proposed system operates in an entirely non-invasive contactless manner providing temperature and/or conductivity variations monitoring and is designed to also provide hyperthermia treatment. In the present paper, the effect of the use of patch antennas as receiving antennas on the system's focusing properties and specifically the use of phased array setups to achieve scanning of the areas under measurement is investigated. Extensive simulations to compute the electric field distributions inside the whole ellipsoidal reflector and inside two types of human head models were carried out using single and two element microstrip patch antennas. The results show that clear focusing (creation of "hot spots") inside the head models is achieved at 1.53GHz. In the case of the two element antennas, the "hot spot" performs a linear scan around the brain area of interest while the phase difference of the two microstrip patch antennas significantly affects the way the scanning inside the head model is achieved. In the near future, phased array antennas with multiband and more elements will be used in order to enhance the system scanning properties toward the acquisition of tomography images without the need of subject movement.**

I. INTRODUCTION

A Microwave Radiometry Imaging System (MiRaIS) has been developed and experimentally used the past 6,5 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 achieve beamforming and focusing on the brain areas of interest. MiRaIS has been used in various experiments in order to evaluate its future potential as an intracranial imaging device [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]. It has been also used in human experiments in order to explore the possibility of passively measuring brain activation variations that are possibly attributed to local conductivity changes. The results indicate the potential value of using focused microwave radiometry to identify brain activations possibly involved or affected in operations induced by particular psychophysiological tasks [1], [2]. Finally, the experimental use of the MiRaIS has also provided preliminary results regarding the occurrence of possible temperature and/or conductivity changes induced by the use of mobile telephony [9].

During the aforementioned research, a number of configurations, in conjunction with the implementation of various approaches in order to optimize the system's focusing properties and performance, have been implemented both theoretically and experimentally (e.g. use of sensitive multiband receivers (e.g. [4]), use of matching layers in order to minimize the abrupt change of the refraction index on the head-air interface (e.g. [5]). We have also developed a hybrid system for both diagnosis and treatment [6], [7] as well near field configurations using phased array systems towards the development of more portable solutions [10], [11]. The use of matching dielectric or metamaterial layers surrounding the human head combined with multiband sensitive radiometers have significantly improved the detection depth and spatial resolution of the system [5], [7], [12], [13]. Since, our initial scope was to develop a tomography system, we have been using a motor based mechanism for three-dimensional raster scanning that provides the required tomography images [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. In the present paper, we investigate for the first time the effect of the use of patch antennas as receiving 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.

II. MATERIAL 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

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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 characteristic, 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).

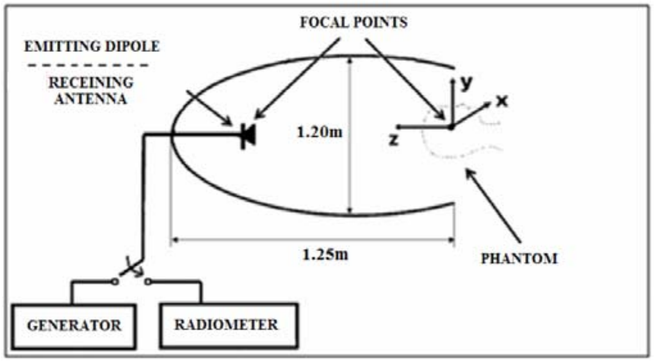
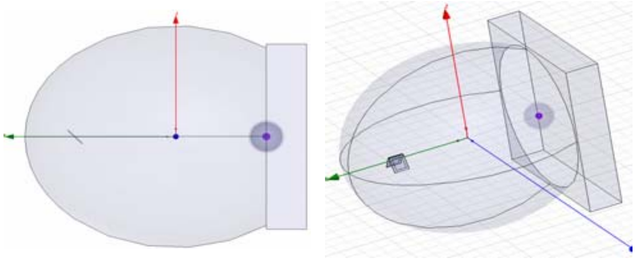


Figure 1. The Hybrid MiRaIS for monitoring and treatment

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. According to the reciprocity theorem, a response of a system to a source is unchanged when source and measurer are interchanged. 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. Hence, 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) [14]. The aim is to investigate the effect of the use of patch antennas as receiving antennas on the system’s focusing properties and specifically the use of phased array setups to achieve scanning of the areas under measurement. It is the first attempt to use directive antennas in the ellipsoidal reflector since only omnidirectional antennas have been used in all previous studies.



a b

Figure 2. The system configuration comprising the conductive ellipsoidal cavity, the head model placed at one focal area with (a). a microstrip patch emitting antenna and (b). two element patch antenna, placed at the other focal area.

The simulations presented in Section III have been performed using two antenna setups: a microstrip patch antenna placed at the ellipsoidal focus point forming an angle of 45° with the horizontal axis (Fig.2a) and a two element microstrip patch emitting antenna comprising placed at the ellipsoidal focus forming an angle of 60° with the horizontal axis (Fig. 2b) [15]. 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 $\Delta\varphi$. 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 1.53GHz with dimensions 100 mm x 90 mm (substrate), 74 mm x 62 mm (patch) on dielectric Rogers RT/duroid 5880, with dielectric constant ε_r = 2.2 and thickness of 3.2 mm. A coaxial feed has been used and the feed is done at d = 21.63 mm from the antenna patch center along the main diagonal.

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. Both models are single layered having dielectric permittivity and conductivity mean values for brain grey matter at 1.53GHz [16], [17]. Both head models are surrounded by a matching lossless dielectric material of ε_r= 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].

III. SIMULATION RESULTS

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 one and two 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 1.53GHz.

A. *Spherical head model*

The electric field distribution inside the ellipsoidal in the case of a single microstrip patch emitting antenna and a spherical head model with a surrounding matching dielectric layer is depicted in Fig. 3. A magnification of the head model where clear focusing of the energy is achieved can be observed in Fig. 4. The radius of the focusing area is approximately 5mm and is achieved at 1cm distance away from the focus along the horizontal x-axis (Fig. 4).

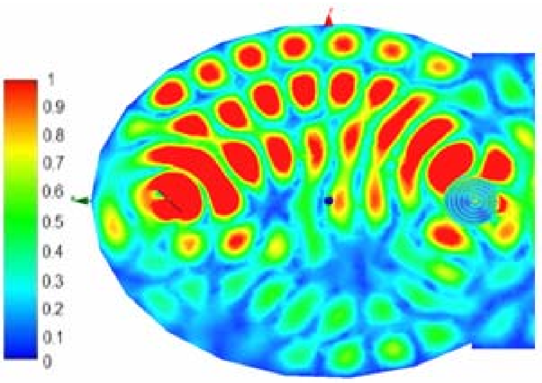


Figure 3. Field distribution inside the cavity and the spherical head model with dielectric surrounding matching material in the case of a microstrip patch emitting antenna operating at 1.53GHz.

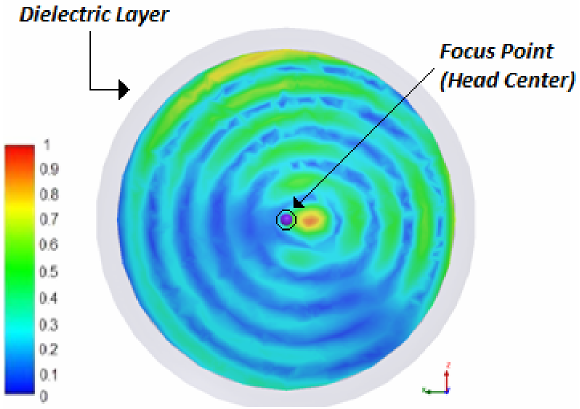


Figure 4. Field distribution inside the spherical head model with dielectric matching layer. The head model is centered at the focal point of the ellipsoidal.

Following, simulations combining a two-element patch phased emitting antenna with the inherent geometrical optics-based focusing properties of the ellipsoidal cavity, were carried out.

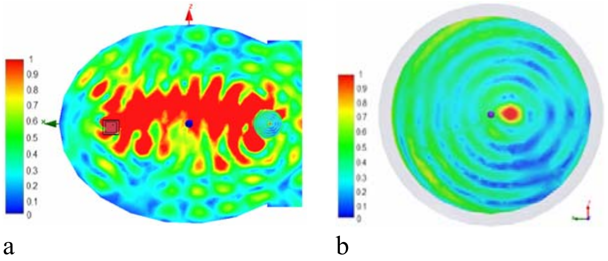


Figure 5. Field distribution inside the ellipsoidal (a) and the spherical head model with dielectric matching layer (b) in the case of the two element phased antenna array. The head model is centered at the focal point of the ellipsoidal.

The results for $\Delta\varphi=30^{\circ}$ show that once more a clear focusing area is achieved inside the head model, which interestingly moves along the horizontal axis performing scanning of 20 mm starting at a distance of 5mm from the focal point (Fig. 4). The radius of the spherical energy focusing area ("hot spot") is 5 mm. For various values of Δφ (45°, 60°, 90°) similar linear scanning is achieved covering an area of the same volume but is displaced several millimeters along the horizontal axis.

B. *Anatomic head model*

The same simulations with the two-element phased antenna were carried out with the use of the SAM head model with phase difference between the two radiating elements $\Delta\varphi=30^{\circ}$ (Fig. 6).

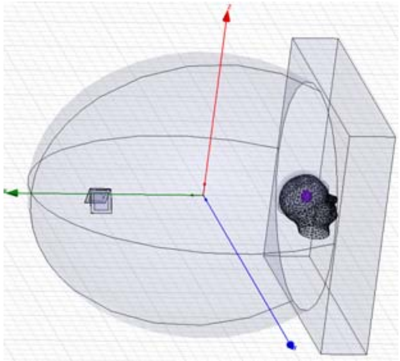


Figure 6. System configuration with two-element phased antenna and SAM head model at 1.53GHz

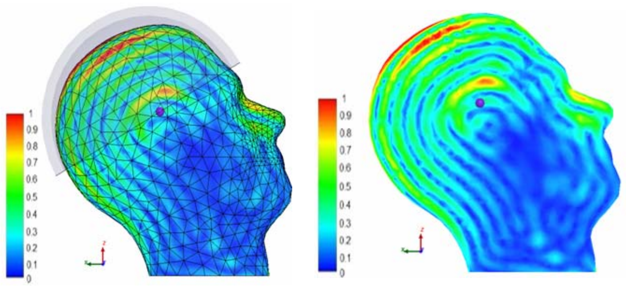


Figure 7. Field distribution inside the SAM head model with surrounding dielectric matching layer. The SAM model is centered at the focal point of the ellipsoidal.

As also observed in the case of the spherical model, clear focusing of the electric field distribution is achieved inside the anatomic head model at a distance of 10mm from the ellipsoidal focus but having a smaller radius (4 mm). Once again, linear movement of the "hot spot" is achieved along the Z axis for 20mm starting at a distance of 10mm from the focal point (Fig. 7).

The phase difference of the two microstrip antennas significantly affects the way the scanning inside the head model is achieved. For example, for Δφ=60° linear scanning along the Z axis is achieved for approximately 12mm. The worst focusing and scanning is observed when Δφ=90°.

High values of electric field distributions are observed on the more superficial brain areas as well as in the surrounding matching material. This is an issue that in the case of hyperthermia may be solved with appropriate and efficient coolling, while in the case of radiometry monitoring, the detected signal will only emanate from the brain area where focusing is achieved and not from the dielectric material.

IV. DISCUSSION AND CONCLUSION

In the present paper, we investigate for the first time the effect of the use of patch antennas as receiving antennas on the focusing properties of a microwave radiometry imaging system and specifically the use of phased array setups to achieve scanning of the areas under measurement.

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 one and two 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 in the case of the two element phased antenna, interestingly moves performing a linear scan of 20 mm, approximately starting at a distance of varying from 5mm to 10mm away from the ellipsoidal focal point. The phase difference of the two 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 without moving the subject.

More simulation scenarios will be investigated following various combinations of phased antenna arrays 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 and more elements will be used in order to enhance and increase the dimensions and scanning of the focusing area toward the acquisition of tomography images without the need of subject movement.

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