A New Metasurface-Enhanced Microstrip Patch Antenna for Haemorrhagic Stroke Detection

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Abstract—This paper presents a new printed square monopole antenna (PSMA) for haemorrhagic stroke detection, enhanced by a metasurface (MTS) superstrate. To show the capabilities of MTS technology in microwave brain imaging, three different tomographic systems are compared in CST Microwave Studio. Our previous developed headband scanner operating in a lossy matching medium is compared to two brain scanners operating in air: a 8-PSMA system and a 8-MTS-enhanced PSMA system. For image reconstruction we used the distorted Born iterative method (DBIM) combined with two-step iterative shrinkage/thresholding (TwIST) algorithm. Our results indicate that a blood-mimicking target placed inside the brain volume of our head model can be detected avoiding the use of a liquid and bulky matching medium. In addition, our MTS superstrate enhances the antennas' reflection coefficient and increases the signal difference due to the presence of the target, which translates into more accurate reconstructions. Thus, MTS technology may be a significant hardware advancement towards the development of functional and ergonomic MWI scanners for haemorrhage detection.

Index Terms—metasurface, antennas, microwave brain imaging, tomography.

I. INTRODUCTION

Haemorrhagic stroke is the second most common subtype of stroke and happens when an artery inside the brain bursts, causing bleeding within the brain [1]. This is a critical disease and wrong medical analysis could be fatal for the patient.

The existing imaging methods to detect intracerebral haemorrhage are not portable and can not be used to monitor the patient in real time. Microwave imaging (MWI) is a good candidate for this purpose and has attracted the interest of many groups [2], [3], [4]. Although its resolution is lower than magnetic resonance imaging (MRI), ultrasound, and X-Ray imaging, MWI presents many advantages [5]. In particular, it is cost efficient, non-ionizing and non-invasive [6].

A functional MWI brain scanner must include specific hardware characteristics. For instance, small and compact antennas operating below 2 GHz are required and the use of a matching medium is recommended [7]. In addition, our previous studies have shown that metamaterial (MM) technology may be a great advance towards the development of MWT systems [8]. Indeed, a MTS-based antenna can take advantage of the MTS’s ability of improving the characteristics of systems for radiating and scattering applications [9]. In particular, over the past several years, artificial materials have become popular in antenna design, as they can overcome limits usually associated with electromagnetic (EM) problems. For instance, zero-index MMs (materials with \( \epsilon \) and \( \mu \) of zero or near zero values) can be used to achieve high directivity antennas [10]. This is because epsilon-and-mu-near-zero media interact with the emitting source, resulting in unusual radiation characteristics [11].

This study investigates the feasibility of designing a more compact and ergonomic brain imaging scanner without employing a lossy matching medium, which is typically heavy, thick and bulky. Thus, a new antenna element and array design operating in air is proposed. In addition, we examine whether MM technology can enhance the “weak” signal scattered from a blood-like target. This signal enhancement is the deciding factor for the use of a specific antenna design for our near-field medical imaging application of interest.

This paper is structured as follow. Section II reviews the proposed PSMA, the MTS superstrate and the three MWI systems investigated in this study. Section III presents and discusses the results, and finally, Section IV concludes the work.

II. MATERIALS AND METHODS

A. Printed Square Monopole Antenna

The proposed PSMA is shown in Fig. 1. The antenna was modelled in CST Microwave Studio. It is based on a square patch with a partial ground on the back side and was designed on an Rogers RT5880LZ low-dielectric substrate (thickness = 1.0 mm, \( \epsilon' = 2, \tan\delta = 0.0021 \)). The antenna is fed using an SMA connector connected with a transmission line. The dimensions of the substrate, patch, transmission line and partial ground are shown in Fig. 1. The reflection coefficient of the antenna measured in free space is plotted in Fig. 2b (dotted lines). The S11 shows a deep resonance around 1.2 GHz, where it falls below -30 dB.
B. Printed Square Monopole Antenna with Metasurface Superstrate Structure Loading

A MTS superstrate structure was modelled to operate as an enhancer of the antenna described above. The MTS unit cell design is based on a perfect conductor (PEC) lattice (thickness = 0.10 mm) printed on a square Rogers RT5880LZ low-dielectric substrate (thickness = 0.6 mm). The metallic pattern design consist of a Jerusalem Cross resonator. A 10×20 unit cell MTS film was used to cover the whole surface of the PSMA. The unit cell and the MTS-enhanced antenna are shown in Fig. 2a. Fig. 2b shows the reflection parameter of the loaded antenna (solid lines).

C. Antenna Systems

Our previous developed microwave tomography (MWT) scanner proposed for microwave head imaging [12], [13] consists of eight spear patch antennas immersed in a 90% glycerol-water mixture and placed elliptically around our anthropomorphic head model. This 3D printed head model is made of nylon and is used as a holder for our liquid phantom that, once solidified, can mimic the brain. Acting both as transmitters and receivers, the eight antennas creates an 8x8 scattering matrix, which is processed by our DBIM-TwIST [14], [15]. To simulate this first setup (“System 1”) in CST Microwave Studio, we used EN 50361 Specific Anthropomorphic Mannequin (SAM) head model. This model includes a nylon layer (\(\varepsilon' = 3.2, \tan\delta = 0.013\)) and average brain tissue inside (\(\varepsilon' = 45.8\) and \(\sigma = 0.76 \text{ S/m}\)). The eight-antenna elliptical array surrounding the head model was immersed in an infinite mixture of our lossy matching medium. This system is shown in Fig. 3a.

Using the same numerical head model, we studied other two microwave brain scanners operating in air: “System 2”, which includes eight PSMA tangent to the head’s surface, and “System 3”, which comprises eight MTS-enhanced PSMA identically positioned (see Fig. 3b).

We have studied the propagation of EM waves for these three antenna arrays and the simplified head model, which includes only nylon and average brain (“no target” scenario) and in the presence of a blood-like target inside the brain volume (“with target” scenario). The blood inclusion is a cylinder of 30 mm diameter and 20 mm height placed in the back side of the brain, close to antennas 1, as shown in Fig. 3.

For each system, the S-parameters were measured over the 0.5–2.0 GHz frequency range and the antennas’ reflection coefficient was obtained. In addition, the signal difference “with target–no target” (dB) at relevant frequencies was calculated.

III. RESULTS

The S-Parameters were calculated via CST simulations over the 0.5-2.0 GHz frequency range for each of the systems described in Section II. Then, the antennas’ reflection coefficient and the signal difference “with target - no target” (dB) at relevant frequencies was plotted.

Fig. 4 shows the reflection coefficient for the antennas placed in position 1 in the systems’ “no target” configuration. As expected, the presence of the MTS superstrate is shifting the resonant frequency of the PSMA towards lower frequencies and improving the S11 parameter of several dB.

Fig. 5 and Fig. 6 show the signal difference “with target – no target” (dB) as a function of the receiver’s location at 1.0 GHz and 1.1 GHz.

As shown in the graph, the presence of the immersion liquid affects the “weak” signal scattered from the target, which also falls below the noise level. On the contrary, when the MTS superstrate loading is present, it leads to an overall improvement of the signal difference compared to the other systems (see transmitter 1). This suggests that the MTS-enhanced PSMA enhances the signal scattered by the blood-mimicking target, which is the signal of interest for our application.

Finally, to assess the possibility of achieving target’s detection with the new developed brain scanners operating in
air, we have applied our 2D DBIM-TwIST algorithm to the simulated data of “System 1”, “System 2” and “System 3”. For the systems operating in air, we carried out multi-frequency (frequency hopping) reconstructions, assuming approximate knowledge of the brain tissue and plastic’s head as initial guess for our DBIM algorithm.

brain imaging scanners, capable of detecting a haemorrhage-mimicking target. To this end, a new array based on eight PSMA operating in air was proposed. Then, to validate the hypothesis that MM technology has the potential to lead to an improvement of the signal scattered from the blood inclusion, which translates into more accurate reconstructions, an enhanced version of the PSMA with a MTS superstrate loading was modelled.

Our results indicate that it is possible to detect a blood-mimicking target placed inside the brain volume of a simple head model without using a bulky immersion liquid. In addition, the signal difference due to the presence of the target is increased in the presence of the MTS superstrate loading.

Our ongoing work is focused on improving the proposed antennas’ designs and developing a more realistic microwave brain scanner to be tested on different setups. In addition, experimental studies to assess the benefits from this approach will be carried on.

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