Compact Wearable Broadband Antenna for Head Microwave Sensing and Imaging

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***Abstract*—Microwave sensing and imaging technologies are gaining interest and reliability in diagnosing and monitoring pathologies in which there is a change in the dielectric properties of tissues, such as stroke, Alzheimer's, and brain tumors in the head. For this reason, there is a need for broadband sensors/antennas working in microwave frequencies to make non-invasive devices able to detect and monitor these pathologies. In this work, we present a flexible and compact antenna optimized for microwave head imaging and sensing, operating in a frequency range of 1.3 GHz−4.7 GHz. It consists of a printed z-shaped monopole with a frontal block of flexible material with custom permittivity and conductivity that improves field penetration into the tissues and reduces the mismatch between the head and the surrounding media.**

***Index Terms*—Microwave sensing and imaging, brain imaging, microwave antennas.**

I. Introduction

In recent decades, the use of microwaves has emerged as a complementary alternative to traditional approaches, such as magnetic resonance (MRI) or computerized tomography (CT-Scan), for detecting and monitoring head pathologies as a non-invasive, harmless, and low-cost technology [1]. Its principle relies on dielectric contrast between healthy tissues and pathologic regions, where field variations are imprinted in both reflection and transmission scattering parameters. Thanks to this variation, inverse scattering imaging algorithms can provide relevant medical information about the region of interest [2].

Among the components of the microwave (MW) system, a main role is played by antenna [3]–[5], which acts as sensors that transmit and receive signals to and from the region of interest, respectively. Their design ensures that the algorithm used provides a good reconstruction of the analyzed scenario [6]–[8]. Antennas that are used for biomedical purposes can be in-body (or implantable), off-body, or on-body, depending on where they are placed in relation to the human body [9]. Thus, the specifications and design procedures will differ and adjust to the challenges imposed by the complexity of EM response in each case. Implantable antennas can be used for data transmission between implantable devices and devices outside the human body, while those placed on the body are used for diagnosis or detection. External ones have the same function as those placed on the body, but suffer from signal reflection at the air-skin interface. In our application, on-body antennas arouse great interest because they guarantee easy positioning and good tissue penetration.

The performance of antennas is strongly related to the dielectric properties of tissues and the geometry of the district of the human body in which they operate. For biomedical applications, having wearable antennas is an important interest, so it could be flexible to better adapt to body surfaces. For this reason, an ad-hoc substrate can be made that also changes the electromagnetic properties of the antenna [10]. Moreover, depending on the target application, the design of the radiating element considers frequency-dependent aspects such as resolution and penetration, considering higher frequencies guarantee better resolution, while lower frequencies allow greater wave penetration.

An analysis is performed about the sensors present in literature, as shown in Table I, focusing on their applications, the frequency band explored, the substrate used, and the reflection coefficient.

This work presents the design and numerical validation of an on-body, near-electric field antenna suitable for medical applications in the vicinity of the head, such as early detection of Alzheimer's disease [11], diagnosis of brain tumors, and detection and monitoring of stroke [2], [3], [12]–[16].

The final optimal design is a compact and wearable ultra-wideband z-shaped monopole antenna with 3 GHz band, center in 1.7 GHz.

In the following, Sect. II describes the steps to arrive at the final antenna design. Sect. III presents the numerical results obtained from a simulation with a block mimicking the dielectric properties of human head tissue. Finally, the

TABLE I: Antennas state of art

Type of antenna	Application	Frequency	Substrate Material	RC*
UWB antenna 45×50 mm [17]	Water based products	1−10 GHz	NA	<-10 dB
Clover structured monopole 50×45 mm [18]	Various SWB application	1.9−30 GHz	FR4	NA
Brick shaped antenna 30×48 mm [19]	Stroke monitoring	0.8–1.2 GHz	CM⋆ ϵ_r=20	<-10 dB
UWB patched antenna 85×35 mm [20]	Stages detection of Alzheimer's disease	1.5–2.1 GHz	Viscose Wool Felt	NA
Implantable loop antennas [14]	Detection of Alzheimer's disease	0.3–1 GHz	FR4	<-20 dB
Compact implantable loop antennas [12]	CSF monitoring	0.1–1 GHz	FR4	<-10 dB
EBG based microstrip patch antenna [21]	Brain tumor detection	$f_R{}^{\dagger}$= 7.3 GHz	Rogers R03003	<-18.4 dB
Compact wideband antenna 24×24 mm [22]	Stroke monitoring	1–4 GHz	RT6010	<-10 dB
Side slotted Vivaldi antenna 45×37 mm [23]	Breast imaging	3.9–9.15 GHz	RT5870	<-10 dB
UWB monopole antenna 38×35 mm [24]	Cancer detection	2.7–22.7 GHz	RT5880	NA
Metamaterial wideband antenna 50×40 mm [25]	Brain tumor detection	1.37–3.16 GHz	RT5880	<-10 dB

* Reflection Coefficient, ⋆ Coupling medium, † Resonance frequency

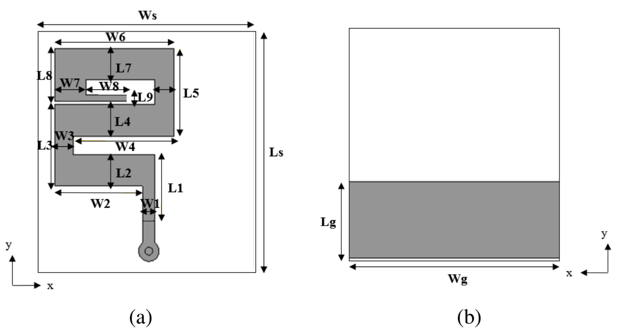


Fig. 1: Front (a) and back (b) of the z-shape antenna.

conclusion and perspectives are discussed in Sect. IV.

II. Design of Antenna and Numerical Validation

The structure of the designed antenna consists of four components: (1) the radiating element, (2) the metallic component responsible for transmitting and receiving signals, (3) the substrate, a dielectric layer that acts as the physical support of the antenna, and (4) a matching layer. It takes the starting point proposed in [24], which is then optimized and adapted to the specific head microwave sensing and imaging applications. The design is a z-shape which is depicted in Fig. 1.

The metal components, the radiating patch and the ground, are modelled as perfect electrical conductors (PEC). The substrate used is Rogers Duroid RT5880® which has ϵ_r=2.20, very low losses. The dielectric thickness is set at 1.575 mm. Due to the interest of our applications involving the positioning of the antennas on the head, it is decided to insert the connector on the back of the antenna, attached to the ground plane and holing the substrate to reach the contact with the microstrip to avoid too much stress in the cables.

Initially a rectangular-shaped block of size 60 mm × 80 mm, consisting of 7 layers representing the head tissues with the appropriate dielectric properties (DP) is constructed (see Fig. 2). The DP of all the tissues are shown in Fig. 3. The layers have the thickness of real human head tissues. As a first approach, to test the performance of the antenna, it is decided to use a simplified model in order to have simpler and faster simulations.

Here, we use a gradual multi-step design methodology, which starting from an analysis of the geometric features and their effect on the scattering of the antenna, get to a study of field penetration by changing the dielectric properties of the matching medium (MM). For that, first, we evaluate the best geometry, then, the MM, also analysing surface currents, and finally we bent the block to get a more realistic situation.

III. Results

This section reports the most significant results obtained from the several tests carried out.

1) Geometry: A series of parametric simulations are performed in which the different geometric parameters of the antenna are analysed. The final dimensions are listed in Table II. The surface current distributions are also investigated changing some parameters. Figure 4 shows how the geometric parameters, highlighted in red, most influence the current distribution at three different resonance frequencies (1.5 GHz, 2.4 GHz, 4.1 GHz).

TABLE II: Dimensions (mm) of the antenna.

Label	Value	Label	Value	Label	Value
Wo*	2.4	W3	4	W6	19
Lo*	7.6	L3	12	L7	5
W1	2	W4	16	W7	5
L1	10.6	L4	5	L8	7.5
W2	14	W5	3	W8	8
L2	5	L5	16	L9	1
Ws*	35	Wg*	35		
Ls*	38	Lg*	12.5		

* The subscripts s, g and o refer, respectively, to the substrate, to the ground plane and to the microstrip dimensions.

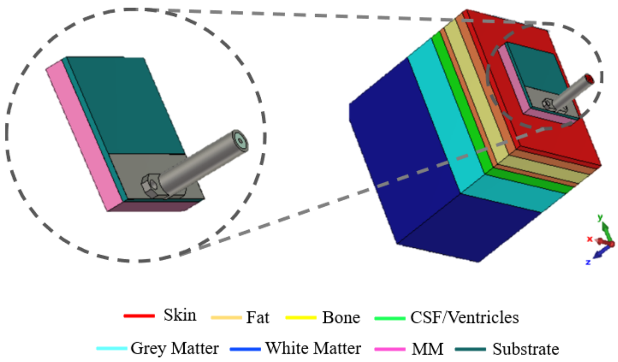
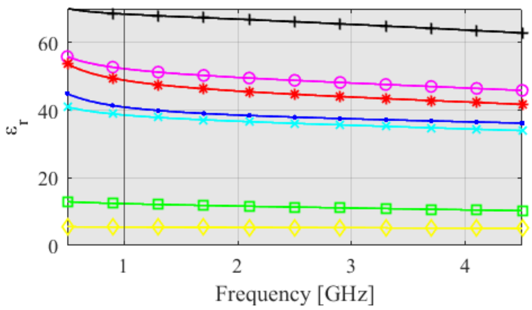
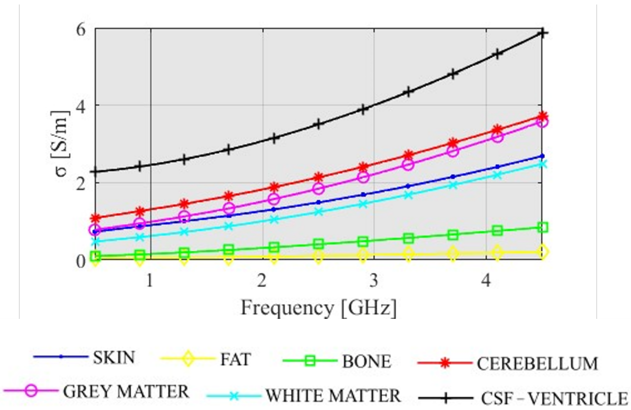


Fig. 2: Antenna with MM and a multi-layer block simulating the head.

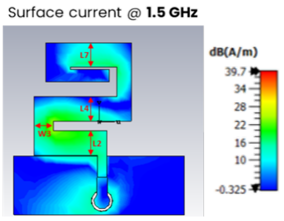


(a)

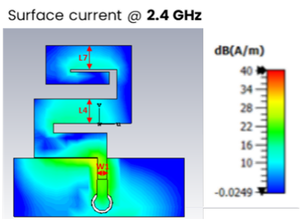


(b)

Fig. 3: Dielectric properties of the head tissues: these are the nominal values obtained from [26]; (a) permittivity and (b) conductivity.



(a)



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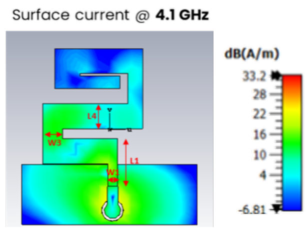
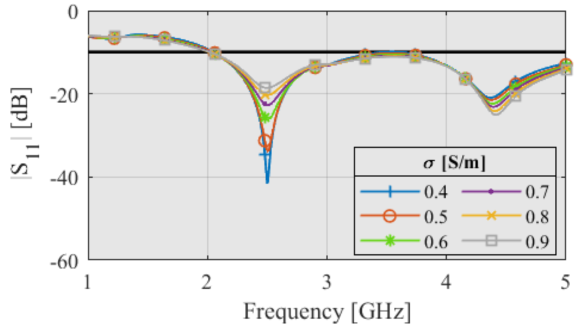
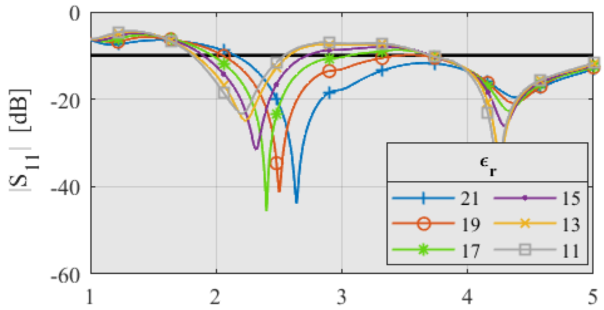


(c)

Fig. 4: Surface currents distribution at the resonant frequencies and parameters that are influenced by (in red).



(a)

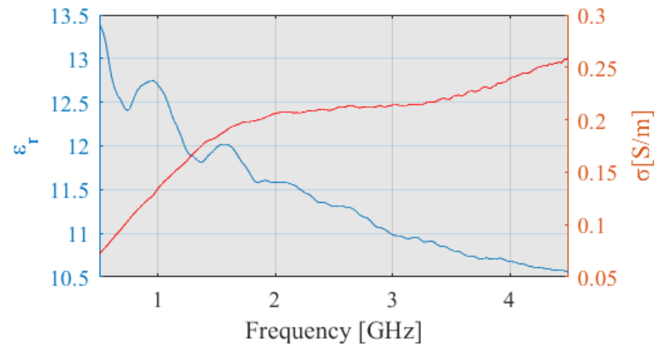


(b)

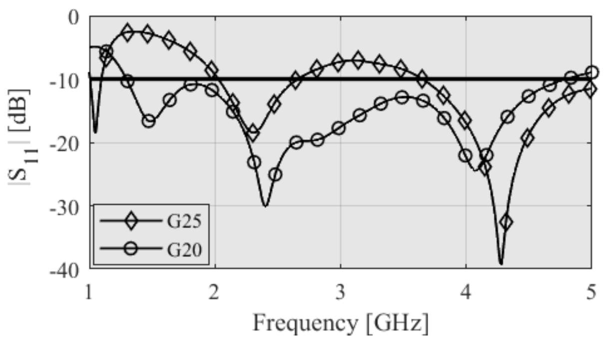
Fig. 5: Conductivity (a) and permittivity (b) influence on the reflection coefficient.

2) Matching medium influence: To improve the wave penetration in the head tissues and to couple the antenna with the body, matching mediums are often used between the antenna and the head surface, such as mixtures of water and glycerine [27] or Triton X−100 [28]. However, this solution is inconvenient for medical applications regarding portability, which is why solid matching mediums made of e.g. mixtures of urethane rubber and graphite powder are also used [3]. To guarantee a certain resonance and good penetration, several tests are carried out by changing the dielectric properties of the MM. First, we performed parametric simulations by varying the conductivity and permittivity of the MM, keeping constant values in frequency. From Fig. 5, it can be seen the results obtained. To keep the wide band, a trade-off with the magnitude at the higher resonant frequency is needed. For this reason, the best value is ϵ_r= 21. Subsequently, different MM materials are simulated with frequency-varying DP; the starting point is [29], from where DP of materials made in the laboratory with mixtures of urethane rubber and graphite powder are taken. The materials chosen turned out to be flexible in such a way as to be easily adaptable to the head and simple to fabricate. Figure 6 shows the frequency trends of the MM DP that gave better results and the reflection coefficient (S11) obtained, compared to an S11 achieved with a MM with higher DP: it can be seen that the bandwidth is now between 1.3 GHz and 4.7 GHz.

3) Block bending: To best mimic the real human condition, the rectangular model is bent with a radius of curvature of 85 mm. Since the Rogers grade of flexibility



(a)



(b)

Fig. 6: Permittivity and conductivity trend of the best MM made with a mixture of urethane rubber and graphite powder (a) and reflection scattering parameters (b).

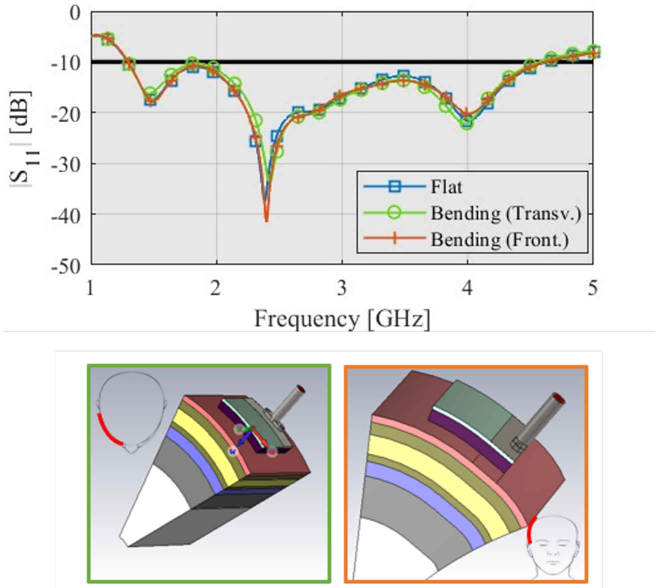


Fig. 7: Bending effects on the reflection scattering parameters. The configuration used is shown below the graph.

is controversial in the literature, two solutions have been proposed: the first involves that the material is flexible and capable of adequate bending, and the second contemplates a matching medium that follows the head curvature applied on the antenna kept flat if the material is not flexible. Both of the solutions (see Fig. 7) demonstrate acceptable robust results, even if, as predicted, the antenna bending would narrow the bandwidth of 1 GHz almost. However, the bent antenna solution is preferred to the other as it is more easy-use and common, as demonstrated in [30]–[35] where the flexibility of the supporting substrate of the antenna is assessed.

Finally, Figs. 8 and 9 show the best S11 achieved and the penetration of the field power at 1.5 GHz, 3 GHz and 4.5 GHz: it is reported to demonstrate the good functionality of the designed antenna since the radiation can reach the CSF even at higher frequencies.

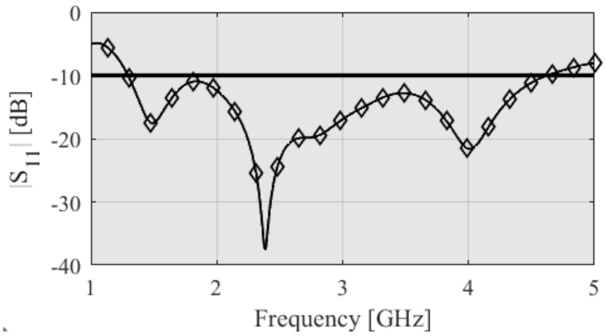
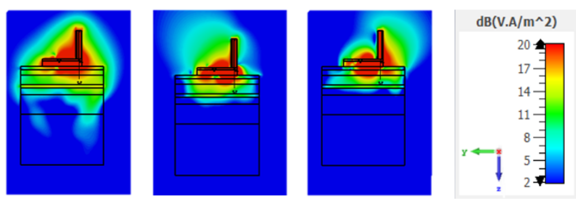


Fig. 8: Final reflection scattering parameter of the antenna: it can see the three resonance frequencies at 1.5 GHz, 3 GHz and 4.5 GHz and the operating frequency range to 1.3 GHz−4.7 GHz.



(a) (b) (c)

Fig. 9: Power flow penetration at a) 1.5 GHz, b) 3 GHz and c) 4.5 GHz.

IV. Conclusion and Perspectives

This work presents an ultrawideband monopolar z-shaped antenna, numerically validated. It has −10 dB bandwidth from 1.3 GHz−4.7 GHz and is capable of achieving sufficient resolution at lower frequencies to detect abnormalities such as stroke or brain tumors and of penetrating up to the CSF tissue for Alzheimer's diagnosis even at higher frequencies. The future perspectives of the current work include antenna manufacturing and testing in a realistic scenario, with e.g., a phantom head.

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