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COMPACT WIDEBAND ANTENNA IMMERSSED IN OPTIMUM COUPLING LIQUID FOR MICROWAVE IMAGING OF BRAIN STROKE

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Abstract—This article reports on the design of a wideband compact microstrip-fed tapered slot antenna aimed at microwave imaging of a brain stroke. The antenna is immersed in a carefully designed coupling liquid that is used to facilitate higher signal penetration in the brain and thus increased dynamic range of the imaging system. A parametric analysis is used to find out the required properties of the coupling liquid. A suitable mixture of materials is then used to implement those properties. In order to protect the antenna from the adverse effects of the coupling medium, dielectric sheets are used to cover the radiator and the ground plane. To verify the proposed design in brain imaging, the antenna is tested using a suitable head model. It is shown that the antenna with a compact size (24 mm × 24 mm) on RT6010 substrate (dielectric constant = 10.2) operates efficiently over the band from 1 GHz to more than 4 GHz with more than 10 dB return loss. The time domain performance of the antenna supports its capability to transmit a distortion-less pulse with a high fidelity factor inside the head tissues.

1. INTRODUCTION

Microwave imaging systems for medical diagnostics have recently been proposed to augment conventional medical imaging systems [1]. Research has shown that there can be significant differences in dielectric properties of normal and abnormal tissues at microwave frequencies [2–6]. This phenomenon is well known in the field of microwave imaging (MI) for breast cancer detection. However, MI

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techniques applied to other tissue abnormalities, stroke detection in particular, are yet to be adequately researched. Potentially, MI offers a diagnostic method with a wide variety of advantages, such as non-ionizing radiation, low-cost portable system and fast imaging results.

A stroke is an abrupt onset injury that affects the central nervous system. It can be classified into two main categories ischemic and hemorrhagic stroke. Ischemic stroke results from blocking the artery that carries blood to the brain. Hemorrhagic stroke results from bleeding within the brain or in the space surrounding. Both medical conditions lead to death in the intermediate future if left untreated. Moreover, the symptoms can be similar between the two conditions, however, the medical treatment is significantly different. An incorrect determination of the type of stroke most certainly leads to the death of the patient.

A clinical decision has to be made within 3 hours of the onset of the symptoms of a stroke to ensure the treatment is effective [7]. It is for these reasons MI systems for stroke detection has gained significant research interest in recent times; examples are found in [3] and [5].

To achieve sufficient penetration in the head tissues, it is believed that the microwave imaging system must operate at approximately 1–4 GHz [3–5]. Thus, a wideband antenna that operates efficiently across that band is a crucial element in the success of microwave imaging system of the brain.

This paper reports the design of a miniaturized tapered slot antenna with an operational band that extends from 1 GHz to 4 GHz. The performance of the antenna is tested via simulations and measurements. The SAM (Specific Anthropomorphic Mannequin) head model [8] is used in the simulations to test the proposed antenna. Both the antenna and the head phantom are immersed in a coupling liquid to improve the signal penetration. Since the post-processing of scattered microwave signals in brain imaging generally requires time-domain signals, the fidelity factor of the transmitted time-domain pulses from the antenna into the coupling medium is examined.

2. ANTENNA AND COUPLING MEDIUM DESIGN

Different types of antennas have been previously designed to operate in imaging systems [9–11]. In this paper, the utilized antenna is aimed to be compact in size, possess directional properties and provides resonance across the desired frequency band. Fig. 1 shows the configuration of proposed tapered slot antenna which is designed for a microwave-based brain imaging system. It is fed using a microstrip line of 50 Ω characteristic impedance. The slot of the antenna is tapered

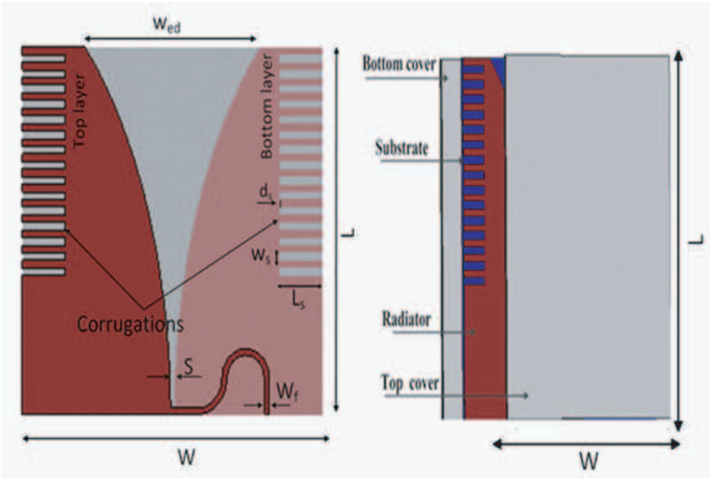


Figure 1. Configuration of the designed antenna (a) without cover, (b) with protecting cover.

using an elliptical function [12, 13]. The antenna is designed using Rogers RT6010 (thickness = 0.635 mm, relative dielectric constant = 10.2) as the substrate. Giving the lowest frequency of operation f_1 and the dielectric constant ε_r, the width and the length of antenna designed using the following equation:

$$W = L = \frac{C}{f_1} = \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

c: is the speed of the light.

The radiating structure of the antenna is the intersection of the quarter of two ellipses with major radii (r_1 and r_2) and secondary radii (r_{s1} and r_{s2}) using the following equations:

$$r_1 = \frac{W}{2} \tag{2}$$

$$r_2 = \frac{W}{2} - w_f \tag{3}$$

$$r_{s1} = L - a \tag{4}$$

$$r_{s2} = 0.5r1 \tag{5}$$

a : is a parameter used to control the frequency of operation.

In the current design$r_1 = 12\,\text{mm}$, $r_2 = 11.55\,\text{mm}$, $r_{s1} = 23.72\,\text{mm}$, $r_{s2} = 6\,\text{mm}$, $a = 0.28$.

Next, a miniaturization technique is used to reduce the size of the structure [14, 15]. The modification from the traditional tapered slot structure starts by removing the tapered ground and the slotline-to-microstrip transition. A direct connection is used to connect the top radiator with the microstrip line, whereas the bottom layer is used as ground plane. The slot s between the top radiator and the ground is used to achieve fine quality matching with the feed point. The feed structure is curved from the edge of the structure to ease the connection of the microstrip line with the external port in the direction that is suitable for the planned imaging system.

A symmetrical corrugation is then used in the outer edges of both the top radiator and the background in order to miniaturize the size of the antenna. Those corrugations are used in order to increase the effective path length of the surface current, and thus, to enable the acceptable performance of the antenna at the low part of the band when the size of the antenna is reduced. It can also help to suppress standing waves arising in the antenna's structure [14].

To reduce the scattered signals at the interface between the antenna and the head tissues, and to achieve the best matching with the tissues, both the antenna and the imaged object are immersed in a coupling medium with a high dielectric constant and low conductive loss [16, 17]. The high permittivity of the liquid can physically reduce the size of the antenna and potentially increase the dynamic range of the imaging system. In order to design a proper coupling liquid, different mixtures were tested. HP85070B coaxial probe is connected to the HP network analyzer (HP8530A) and used to measure the dielectric properties of different kinds of materials. It is found that a mixture of 70% water and 30% of solution that includes the same

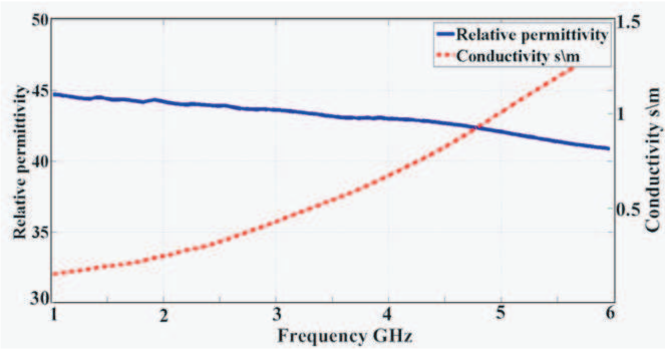


Figure 2. Variation of permittivity and conductivity with frequency for the designed coupling liquid.

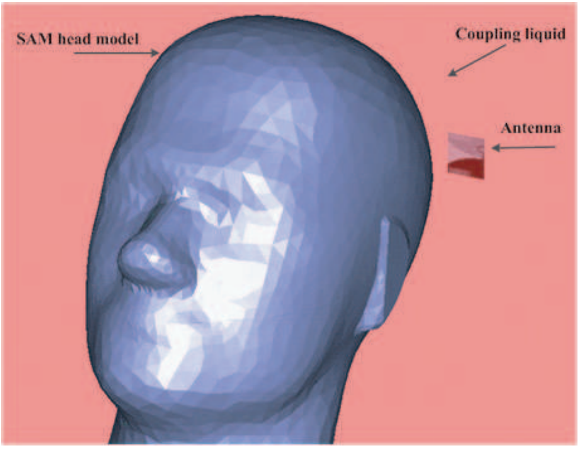


Figure 3. The antenna when used to image the SAM head phantom.

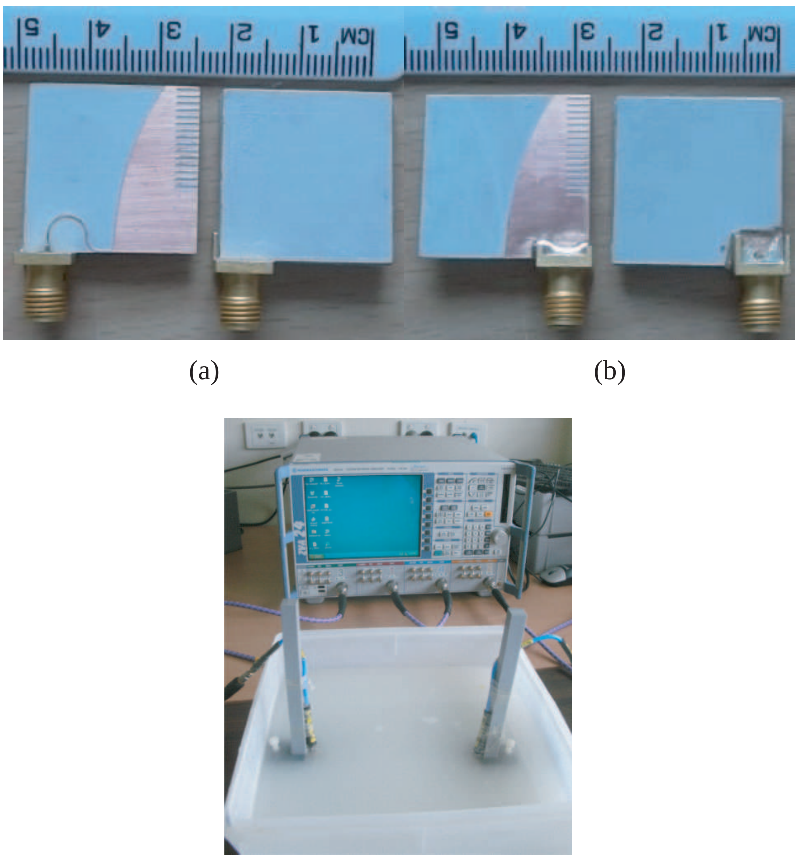
percentage of grape seed oil and polysorbate 80(Tween-80) achieves the best possible matching between the designed antenna and the utilized head phantom. The measured variation of the dielectric permittivity and conductivity of the designed liquid for the frequency range from 1–4 GHz is shown in Fig. 2. In order to optimize the design of the proposed antenna when immersed in the designed coupling liquid, the properties of the manufactured coupling medium is loaded into the simulation tool. The antenna is also tested when operating in front of a realistic SAM head model as depicted in Fig. 3.

In order to protect the antenna from the adverse effects of the coupling liquid, the top radiator and the ground plane are to be covered by a suitable protective material, such as resin or varnish. In the current design, it is covered by a dielectric sheet that has the same dielectric properties of the substrate as shown in Fig. 1(b). An adhesive material that has a dielectric constant close to that of the utilized substrate is used to glue the antenna and the covering sheets together. Given the lowest frequency, the thickness and the dielectric properties of the substrate, the antenna was initially designed according to the guidelines presented in [12]. The length of the slots of the corrugated structure is chosen to be quarter of the effective wavelength calculated at the center frequency of operation. Since the antenna is designed to operate across the band from 1 GHz to 4 GHz, the center frequency is 2.5 GHz. The dimensions of the antenna and the slots are then optimized using CST Microwave Studio. The final dimensions in (mm) are; $S = 0.28$, $w_f = 0.45$, $L_s = 3.5$, $W_s = 0.5$, $d_s = 0.5$, $w = 24$, $L = 24$, and $W_{ed} = 17$.

3. RESULTS AND DISCUSSION

Performance of the proposed antenna is first verified via computer simulations. Next, the antenna is manufactured (Figs. 4(a) and (b)) and tested to confirm its simulated performance. The antenna was tested while immersed in the designed coupling liquid (Fig. 4(c)) with and without the presence of a head phantom.

The simulated and measured return loss of the antenna when immersed in the coupling liquid and without the head phantom is shown in Fig. 5. The obtained results indicate that the antenna has a



(a) (b)

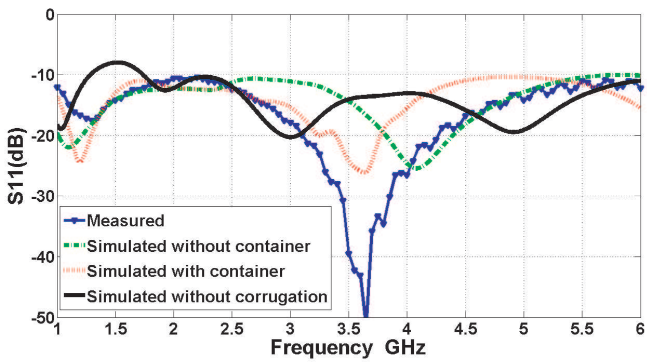
(c)

Figure 4. Photo of manufactured antenna. (a) Top radiator and (b) ground side without and with cover. (c) The test platform with two antennas immersed in the coupling liquid.

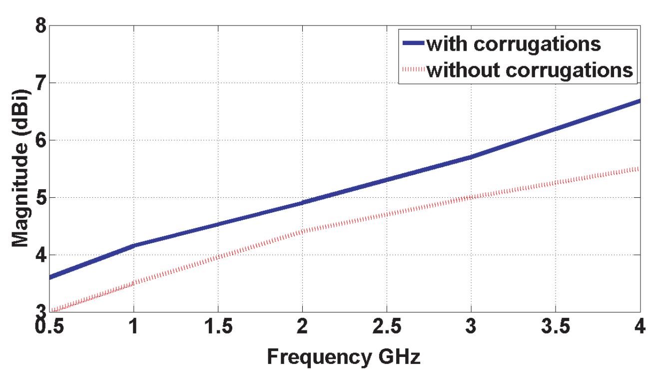
reflection coefficient of less than -10 dB across the required band from 1 GHz to 4 GHz. The plastic container that includes the antenna and the coupling medium has a slight effect on the performance as indicated in Fig. 5(a). To test the effect of the corrugations on the covered band, the reflection coefficient was calculated using the simulation tool for the antenna without corrugations. It is found that the reflection coefficient in that case is less than -10 dB across the limited band from 2.35 GHz to 4 GHz as shown in Fig. 5(a).

To test the directive properties of the antenna, the gain was calculated using the simulation tool. It was found that the gain varies between 4 dBi and 6.7 dBi across the band from 1–4 GHz. Without corrugations, the gain changes between 3.5 dBi and 5.5 dBi across the same band as depicted in Fig. 5(b).

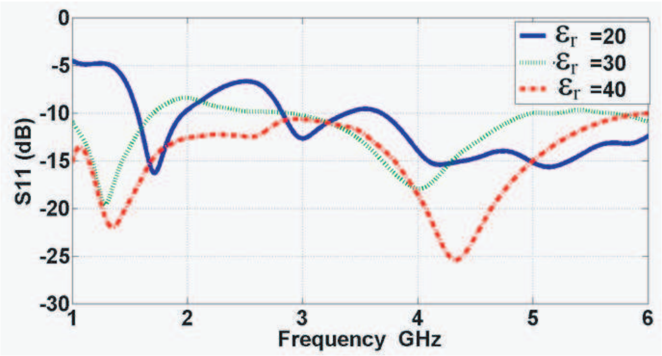
To verify the effectiveness of the chosen coupling liquid that has an average dielectric constant of around 43 as depicted in Fig. 2, the reflection coefficient of the antenna is calculated via simulations for



(a)



(b)



(c)

Figure 5. (a) The measured and simulated reflection coefficient of the antenna when immersed in the designed coupling liquid in the absence of the head phantom, (b) gain of the antenna with and without corrugations, and (c) the simulated reflection coefficient for other coupling liquids.

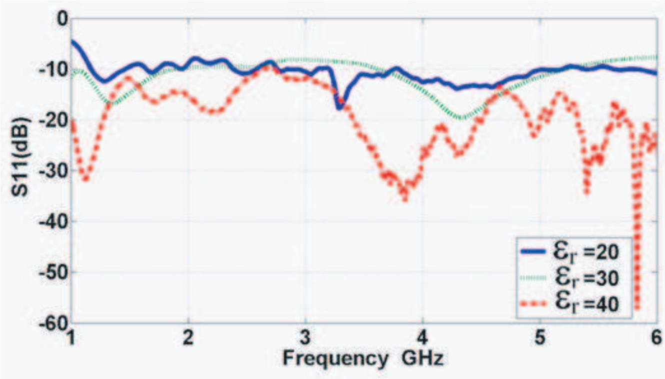


Figure 6. The simulated reflection coefficient of the antenna placed in front of SAM head model and immersed in different coupling liquids with the shown average dielectric constant.

three different types of coupling liquids that have an average dielectric constant of 20, 30, and 40. The result of simulations shown in Fig. 5(c) reveals that the liquid with an average dielectric constant of 40, which is close to that of the fabricated one, enables the antenna to achieve its best performance.

The simulated return loss of the antenna when in close proximity

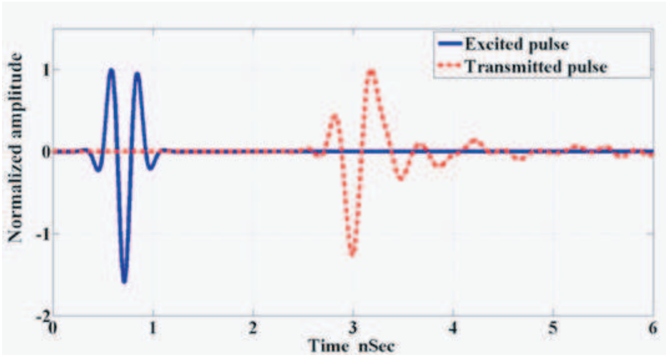


Figure 7. The time domain response of the manufactured antenna.

to the SAM head phantom is shown in Fig. 6. It is clear that the antenna works without any degradation in its performance when using the designed coupling liquid due to the optimum achieved matching.

Recent reported brain imaging systems uses time-domain pulses to reconstruct the image (see for example [5]). For this reason, the time domain impulse response of the antenna is tested to verify its capability to support the transmission/reception of narrow pulses in a distortion-less manner. Two antennas are placed at the same height above the ground with 3 cm distance between them. The two antennas face each other in the end-fire direction. The space between the antennas is filled with the developed coupling liquid. The vector network (R&S ZVA24) is used to generate a narrow pulse with 1–4 GHz frequency content. The pulse transmitted from one of the antennas is received by the other antenna. The measurements are shown in Fig. 7. It is clear the developed antenna supports almost distortion-less transmission which minimises so-called ghost targets occurring in the microwave imaging system. It is worth mentioning that the time delay between the transmitted and received pulses in Fig. 7 is due to the antennas' structure, connecting cables and the 3 cm distance between the end points of the two face-to-face antennas.

To quantify the distortion level in the transmitted pulses inside the coupling liquid, the second antenna is moved away from the first one with different distances so that the variation of the fidelity factor as a function of distance inside the coupling medium can be calculated. The fidelity factor is calculated as the maximum magnitude of the cross correlation between the observed pulse at a certain distance and the excitation pulse [18]. The simulated and measured results are shown in Fig. 8. The results indicate that the fidelity factor of the antenna decreases as the distance from the antenna increases. However, the value is still within the acceptable limit for a successful imaging system (above 50%) as compared with previous reported values [19]. There are some differences between the simulated and measured fidelity factor as depicted in Fig. 8. The effect of the container on the performance of the antennas can be predicted from the simulated results with and without the container in Fig. 8. It is clear that the multiple reflections from the boundaries of the plastic container cause a slight degradation in the fidelity factor.

In order to clarify the importance of using the designed coupling liquid, the fidelity factor is also estimated inside the SAM head model for two cases. First, when the head and antenna are immersed in the developed coupling liquid and the second one when the antenna

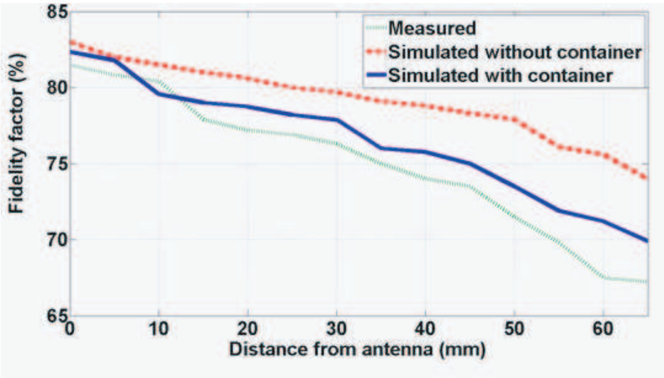


Figure 8. The simulated and measured fidelity factor as a function of distance from the antenna when it is immersed in a coupling liquid.

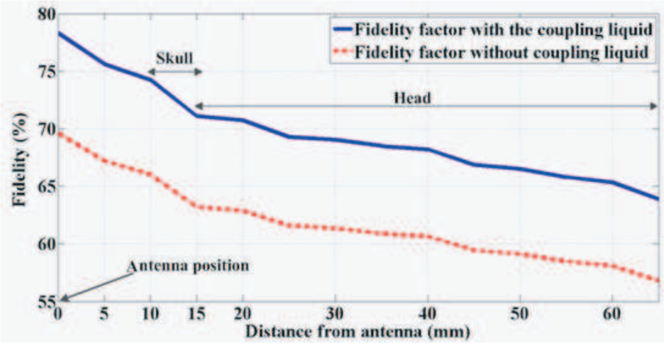


Figure 9. The simulated fidelity factor as a function of distance from the antenna to the SAM head model with and without coupling liquid.

is redesigned to work in free space (without coupling liquid) with dimensions of (99.5 mm $\times$ 99.5 mm). The results depicted in Fig. 9 show that the fidelity factor of the antenna immersed in the coupling liquid is better than its value when no coupling liquid is used despite the need for a larger antenna size in the no-coupling liquid case. For the antenna presented in this paper, the fidelity factor is within reasonable values [19] inside the head phantom when it is immersed in the designed coupling liquid.

From comparing the results of the fidelity factor with (Fig. 9) and without (Fig. 8) the presence of the head phantom, it is clear that the presence of the phantom causes a noticeable reduction in the fidelity factor. This is one of the challenges facing the design of a reliable microwave-based brain imaging system.

4. CONCLUSION

The design of a compact wideband tapered slot antenna immersed in a coupling liquid for the use in a microwave-based brain imaging is presented. The coupling liquid is designed properly to improve the matching between the antenna and the brain tissues using a mixture of water, grape seed oil and polysorbate 80(Tween-80). To miniaturize the antenna, corrugations are introduced in outer edges of both the radiator and the ground plane. To protect the antenna from ill effects, such as corrosion of the conductive layers by the coupling liquid, the antenna is covered by a dielectric sheet. The simulated and measured return loss of the antenna tested with and without a head phantom have shown that the antenna covers the band from 1 GHz to 4 GHz with better than 10 dB return loss across the desired band.

The time domain performance of the antenna has also been studied. It has been shown that, although the fidelity factor decreases as the signal penetrates the head, the value of that factor is still within the acceptable limits when the coupling liquid is used.

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