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A Compact Slot-Loaded Antipodal Vivaldi Antenna for a Microwave Imaging System to Monitor Liver Microwave Thermal Ablation

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ABSTRACT This study presents the design and the experimental validation of a slot-loaded antipodal Vivaldi antenna. The intended use is in an array configuration for monitoring liver microwave thermal ablation by way of microwave imaging (MWI). To optimize electromagnetic power transfer to the human abdomen, the antenna was designed to operate in a coupling medium. The final design has overall dimensions of 40mm×65mm, and the working bandwidth goes from 600 MHz up to 3 GHz, with the possibility to operate at higher frequencies, also. The antenna proposed in this study shows the most compact aperture dimension, as compared with other antennas designed for biomedical applications, working within the same bandwidth. To experimentally evaluate the antenna performances, the coupling medium was realized, proposing a recipe made by low cost, and easy to provide and use, materials. In particular, a mixture of water, oil, dishwashing detergent, and guar gum was used. The realized material showed dielectric properties close to the target ones, proved stability on a 1-week time, and reproducibility against different realizations. The antenna's measured S-parameters well agreed with the simulation result. When locating two antennas in close proximity, as in the MWI array configuration, the results showed good performances towards mutual coupling.

INDEX TERMS Vivaldi antenna, coupling medium, microwave imaging system, microwave thermal ablation.

I. INTRODUCTION

LIVER cancer is among the most common fatal malignancies, accounting globally for 9.1% of all cancer death [1]. Microwave thermal ablation (MTA) is considered an effective way to treat liver malignancy with a minimum invasive approach [2]. The procedure consists of placing a microwave antenna within the tumor to be treated; then, the antenna is fed with microwave power values up to 100 W for a duration of a few minutes (up to 10 min). In the clinical settings, MTA is flanked by conventional imaging modalities, such as ultrasound (US), computed tomography (CT), positron emission tomography (PET), and magnetic resonance imaging (MRI). These imaging systems are used with different purposes: treatment planning, targeting, monitoring, assessment treatment response, and follow-up [3]. However, real-time monitoring of the thermal ablation treatment remains an unsolved issue because all the existing modalities show different flaws when it comes to clinical procedures [3]. Therefore, the real-time assessment of thermal ablation treatments still heavily relies on the clinician's experience [4].

To improve the accuracy of thermal ablation treatments, microwave imaging (MWI) has been proposed as a novel approach for real-time treatment monitoring [5], [6], [7]. Microwave imaging reconstructs the dielectric properties of the target by processing the electromagnetic (EM) field scattered by the investigated tissue. Typical systems exploit multiple antennas that surround the measurement region to achieve a good imaging resolution [8], [9]. As compared to conventional modalities, microwave imaging has a number of attractive features such as portability, non-invasiveness, cost-effectiveness, and non-ionizing nature of the electromagnetic field [8].

In MTA applications of MWI, the dielectric properties of the thermally ablated area, that are different to those before the procedure, are the imaging goal [10]. To this end, an antenna array can be located in close proximity of the human abdomen and used to probe the region of interest [7]. However, in these applications a limited part of the body is available for measurements; accordingly, it is crucial to design an antenna with a compact dimension while maintaining its matching at low frequencies to allow the necessary penetration depth of the EM field. Accordingly, the adopted antennas play a crucial role in the performance of the system. In general, MWI systems demand antennas to be compact and with wide bandwidth, high fidelity, and low cost [11]. In this respect, patch antennas [12], [13] are low-profile antennas that have been used for brain stroke detection. However, they tend to have a narrow operational frequency band. Bowtie [14] and horn antennas [15] are wideband antennas that have been used for breast cancer detection. Their large aperture size limits them to high-frequency applications. Vivaldi antennas [11], [16] are wideband configurations able to overcome the above-stated difficulties, and their end-fire radiation could allow more antenna elements to be placed into an array configuration.

Due to the large difference between the dielectric properties of air and human body tissues, a significant part of the power is reflected at the interface between air and skin instead of penetrating the tissue [17]. Accordingly, to effectively couple the electromagnetic field into the tissues, MWI antennas are usually immersed inside coupling media that have permittivity (ε_r) close to that of the tissues [17]. Such media also allow to scale down the EM wavelength by a factor of $1/\sqrt{\varepsilon_r}$. Hence, they allow decreasing the required antenna dimensions. On the other hand, the choice of the coupling medium should take several aspects into account: constant dielectric properties in the frequency band of interest, low losses, physical stability, non-toxic to humans, cost-effectiveness, and ease of preparation and use.

Up to now, various coupling mediums have been used for MWI systems. Saline [18], a material that is easy to acquire, can help to provide high-resolution imaging thanks to its high permittivity value. Nevertheless, the high conductivity of saline largely attenuates the EM power before it penetrates the target. Thus, it is hardly chosen for body monitoring applications. Vegetable oil [11] and animal fat [19] have low permittivity and conductivity, and are mostly used for breast imaging. In an oil/water emulsion, the low relative permittivity of oil combined with the high permittivity of water allows achieving dielectric properties values in a wide range of values. In [20] a value of $\varepsilon_r = 22.9$, $\sigma = 0.07$ S/m was achieved at 915 MHz, and remained quite constant across the microwave frequency band. The disadvantage of such a medium is its low stability in time because oil and water tend to split up. A pump must be used to continuously circulate the mixture, thus avoiding the water phase to separate from the oil one [20]. Acetone [21], similar to water/oil emulsion, has low conductivity. However, it could irritate human skin, and it is not clinically safe. Other water-soluble materials, such as corn syrup [22], glycerin [23], Triton X-100 [24], sodium metasilicate gel [25], whose permittivity could be tuned with water to achieve the desired values, have high conductivities, which lead to lossy mixtures. Recently, a low conductivity solid coupling medium was developed for brain stroke imaging [12]. The medium is a mixture of urethane rubber and graphite powder. The dielectric properties are around $\varepsilon_r = 19$, $\sigma = 0.2$ S/m at 900 MHz. The antennas are embedded inside the solid rubber, and they surround the head phantom like a helmet. Such a medium is physically stable, which is suitable for wearable devices. The disadvantage of such a solid medium is due to the complex preparation process [26].

In this paper, both the coupling medium and antenna to be used in a microwave imaging system to monitor liver MTA procedures were designed, realized and experimentally verified. The design specifications, derived to optimize the MWI performances, were presented in [6]. The coupling medium was realized using low-cost and easily available materials. The medium's stability in time was tested. The antenna is a slot-loaded Vivaldi antenna. With respect to the antenna presented in a previous paper [6], the one here proposed shows more compact dimensions. The antenna's performance was characterized both as a standalone antenna inserted in the coupling material, and in an array configuration.

II. MATERIALS AND METHODS

Figure 1 shows the scheme of a MWI system to monitor liver ablation. A MW antenna is placed in the liver tumor to perform the ablation treatment. The treatment is monitored by a MWI antenna array, located close to the abdomen and immersed inside the coupling medium. In [6], design guidelines were derived for both the MWI array and the coupling medium. In particular, it was found that the useful working bandwidth for the imaging system is between 500 MHz and 2 GHz. Additionally, the medium that would properly couple the radiated electromagnetic field to the tissues of the abdomen region was identified as a material with a permittivity of 23.

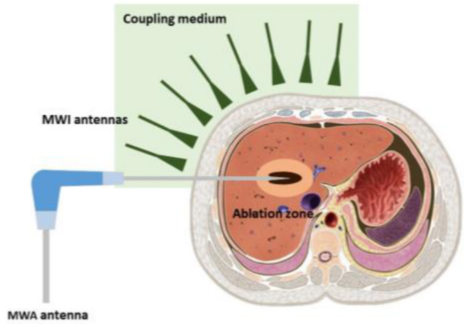


FIGURE 1. Scheme of the proposed Microwave Imaging system to monitor liver ablation (light green: coupling medium).

TABLE 1. Coupling medium recipe.

Components	Ratio by weight
distilled water	37.80%
sunflower oil	57.84%
guar gum	0.42%
dishwashing detergent	3.94%

In the following, the design, realization, and characterization of the coupling medium, as well as of the MWI antennas is presented.

A. COUPLING MEDIUM DESIGN AND REALIZATION

As recalled before, the imaging system should be realized within a coupling medium with relative permittivity of about 23 and negligible losses in the frequency band from 500 MHz to 2 GHz. Such permittivity value was achieved in [20] with a mixture of water, oil, and surfactant. However, as previously stated, the mixture in [20] is not stable in time and needs continuous stirring to avoid separation between water and oil. In this paper, the mixture in [20] is improved by adding guar gum as a thickening agent to increase the fluid viscosity and, as such, solving the separating issue between the phases of the mixture (water and oil). The components making the coupling medium, given by weight, are reported in Table 1.

The preparation procedure of the coupling medium works as follows: first, fill a container with distilled water, then smoothly sprinkle the guar gum powder on the surface of the water. Gently stir the mixture with a stick until the guar gum powder is dissolved in the water, taking care of avoiding air bubbles during this process. If any lump remains undissolved, use a sieve to remove it. Then add dishwashing detergent into the solution and gently mix it. Finally, add the sunflower oil into the mixture and stir it until all ingredients are well incorporated.

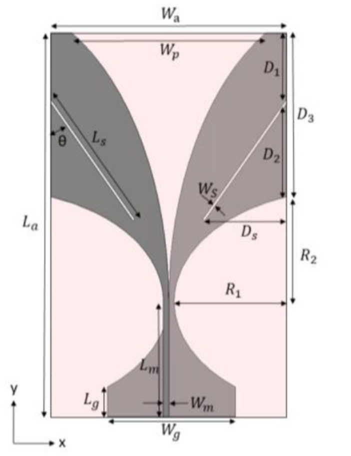
The coupling medium was realized by using the ratio of components in Table 1. The dielectric properties of the mixture was then measured, to verify the achievement of the target values, as well as reproducibility and stability in time.

The dielectric properties of the coupling medium were measured with the open-ended coaxial probe technique. As it is shown in Figure 2. The measurement set-up was made by the Keysight high-temperature probe (Keysight 85070E) connected to a vector network analyzer (P5002A Keysight Streamline, 9 kHz to 9 GHz). Overall, 201 frequency points were measured from 500 MHz to 3 GHz. The measurement uncertainty of the system is 5% [27]. To verify whether the coupling medium's dielectric properties were stable in time, the medium was measured three times in a one-week observation time. The first measurement (day 0) was performed right after the preparation of the coupling medium. The second measurement was performed 24 hours (day 1) after the first measurement, and the third measurement was performed 7 days (day 7) after the first measurement. The coupling medium maintained unchanged its features in a one-week time, and it was not mixed again before each measurement.

FIGURE 2. Measurement experimental set-up.

B. ANTENNA DESIGN AND REALIZATION

In [6], the working conditions of a microwave imaging system to monitor thermal ablation of the liver were defined. In particular, a 0.5-2 GHz frequency band was settled. These conditions give a trade-off between penetration depth, imaging resolution, and antenna dimensions. In the same work, three different Vivaldi antennas were designed and their performances numerically compared. In this work, a new design for the antenna of the MWI system is proposed. The design steps follow the same phases as the antennas proposed in [6], [16], but consider a different antenna substrate and the addition of a slot to allow antenna miniaturization (Figure 2). The chosen substrate is Arlon AR1000, with a relative permittivity $\varepsilon_r = 9.8$, a thickness of 1.575 mm (0.062"), and a conductive copper layer thickness equal to 0.035 mm. Additionally, to further reduce antenna's dimensions with respect to those proposed in [6] and [16], miniaturization techniques were applied. In particular, after a first design on the Arlon substrate, the antenna's width was trimmed by 20 mm (dimension Wa in Figure 2). This step reduced the antenna's aperture in front of the human abdomen region from 60 mm down to 40 mm. However, it also reduced the antenna's electrical length, hence shifting the antenna's lowest working frequency towards higher frequencies. To



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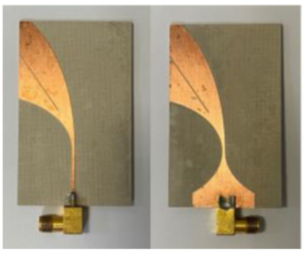

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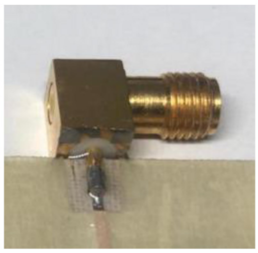


(c)

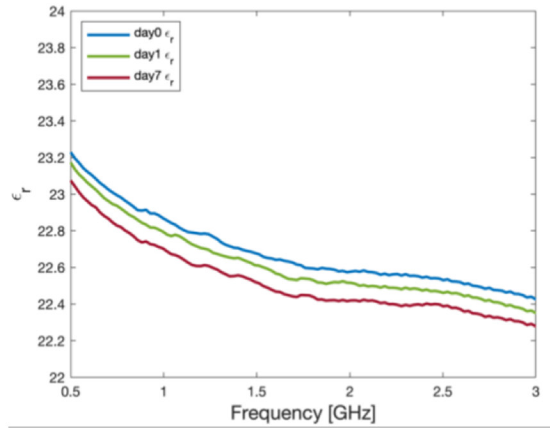
FIGURE 3. (a) Slot-loaded antipodal Vivaldi antenna geometry (gray: metallic layer, pink: antenna substrate); (b) Fabricated antenna sample; (c) connector pin covered by epoxy resin.

TABLE 2. Dimensions of the antenna.

Parameters	Value [mm]	Parameters	Value [mm]
W_a	40	L_a	65
W_p	32.9	L_g	5
W_g	21.7	L_m	19.5
W_m	0.9	L_s	24.9
W_s	0.4	D_1	11.2
R_1	19.1	D_2	15.8
R_2	17.8	D_3	27.7
θ	35°	D_s	14

maintain the antenna's lowest working frequency as close as possible to 500 MHz, a slot was etched in the middle of the radiator and the ground plane to elongate the current path. The presence of a slot can increase the electrical length of the antenna without increasing its physical size [28]. The slot width, length, and position were not chosen arbitrarily. These parameters were selected after a sweeping analysis to pinpoint the influence of the different slot geometrical characteristics on the antenna's matching. In particular, simulations were performed with the parameter sweep function of the CST software (Dassault Systèmes, Vélizy-Villacoublay, France) on the following parameters: R_1, R_2, D_1, D_s, θ, L_s, W_p, W_s (see Figure 3). Finally, the antenna's substrate length was extended of 5 mm to safely solder the SMA connector. The resulting antenna's dimensions are listed in Table 2.

The fabricated antenna (ERMIAS Lab at University of Calabria) is shown in Figure 3 (b). In [6], it was observed



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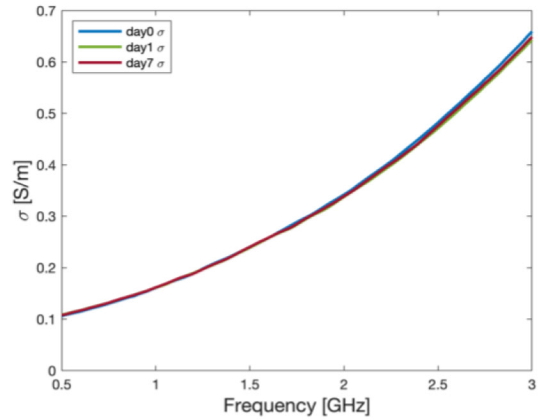


(b)

FIGURE 4. Measured coupling medium dielectric properties: (a)relative permittivity; (b)conductivities.

that the antenna becomes mismatched when located inside the coupling medium and fed by an SMA connector, which is designed to work in air. This mismatching problem was solved covering the connector pin with epoxy resin, whose relative permittivity value is around 4. This method can effectively isolate the connector pin from the coupling medium (see Figure 3 (c)). The sensitivity study carried out in [6] shows that the dimension of the epoxy resin does not impact too much on antenna matching.

The experimental validation of the designed antennas was performed connecting the antenna to the VNA (P5002A Keysight Streamline, 9 kHz to 9 GHz) and placing the antenna in the coupling medium, both considering a single antenna and two closely located antennas.

III. RESULTS

A. COUPLING MEDIUM DIELECTRIC PROPERTIES

The coupling medium's dielectric properties were measured on three different days to verify its' stability.

Figure 4 demonstrates the medium properties measured on different days. It is found that in the frequency band of interest the relative permittivity of the medium is close to the target value $\varepsilon_r = 23$ on day 0. In particular, at 915 MHz, values of $\varepsilon_r = 22.9$, $\sigma = 0.13$ S/m are achieved, which

TABLE 3. Average values in the 500 MHz - 3 GHz band of the dielectric parameters of the coupling medium.

Relative permittivity ε_r		Conductivity σ [S/m]	
Mean	STD	Mean	STD
22.61	0.08	0.32	2.8×10^{-3}

TABLE 4. Absolute differences of the average values of the coupling medium dielectric properties between different days in a one-week time.

ε_r absolute difference		σ absolute difference	
Day 1	Day 7	Day 1	Day 7
0.3%	0.7%	1.43%	0.99%

TABLE 5. Tanks and their dimensions.

Tank Type	Dimensions
Tank A	140mm×140mm×140mm
Tank B	180mm×180mm×180mm
Tank C	220mm×220mm×220mm

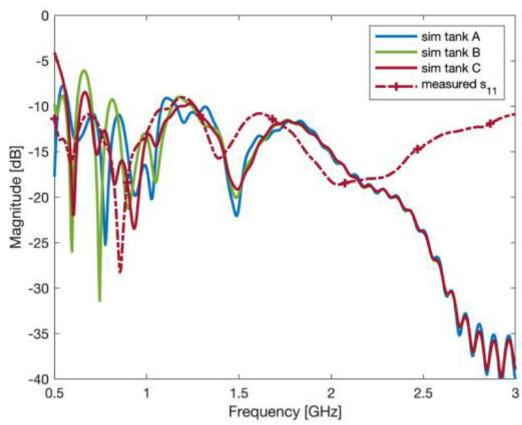


FIGURE 5. Simulation results of one slot-loaded antipodal Vivaldi antenna inside different tank A, B, C and the antenna's measurement result.

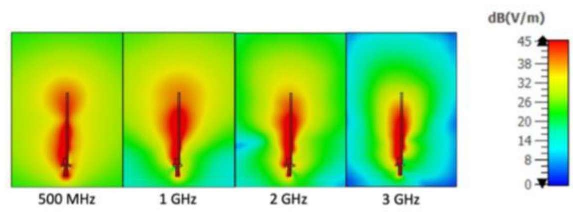


FIGURE 6. Slot-loaded antipodal Vivaldi antenna's E-field distribution in the coupling medium at different frequencies.

are close to the dielectric properties proposed in [20]. In particular, it is interesting to note the decrease of the relative permittivity with increasing time, most likely linked to the loss of water content, notwithstanding the sealing of the mixture container.

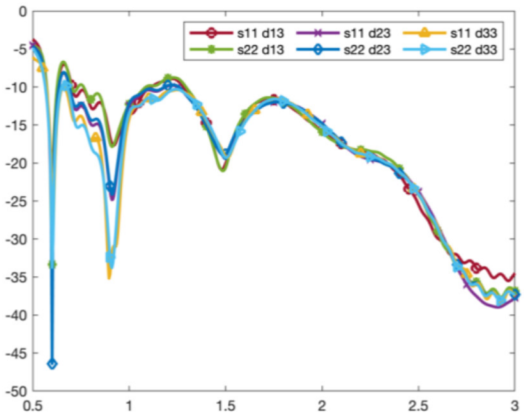
Table 3 reports the mean values and standard derivation of the coupling medium dielectric properties in the frequency band of 500 MHz – 3 GHz measured on day 0. It is found from the table that the mean value of the coupling medium's dielectric properties is close to the target value. The STD of the dielectric properties is lower than 0.1. The changes in the measured values on day 1 and day 7 with respect to the values right after the mixture realization are reported in Table 4 as the mean difference computed from 500 MHz to 3 GHz. From Table 4, it is found that the variation of the medium dielectric properties is below 2%. As a whole, it can be stated that the coupling medium's dielectric properties are stable in a 1-week observation time. This study only investigates the coupling medium's properties within a week rather than a longer time, as it was observed that water and oil in the coupling medium slightly separate after a month. Therefore, the medium should be mixed again before the experiment, if it is preserved longer than a week, and it is not recommended to use the coupling medium for longer than a month due to the lack of preservative in the recipe.

B. ANTENNA PERFORMANCE

In order to validate the antenna performances inside the coupling medium, the antenna's matching was simulated considering the antenna located inside a tank filled with the coupling medium, considering different tank's dimensions. It is worth mentioning that the simulation takes into account the measurement properties of the medium; in particular, medium properties with the mean measurement value on day 0 were considered. The tanks and their dimensions are given in Table 5. The simulated antenna S-parameters are shown in Figure 5. It is found that the dimensions of the tank mainly influence the antenna's matching at lower frequency (below 1 GHz), while the antenna matching rarely changes above 1.5 GHz. It is worth noticing here that at 1 GHz the wavelength in the coupling medium is about 60 mm. Accordingly, having located the antenna in the centre of the tank, its distance from the later wall is about 1 wavelength in Tank A while it increases up to about 2 wavelengths in Tank C. It is found from the figure that the antenna's performance is better when working inside a larger tank (tank C), since the antenna lose its matching around 1.2 GHz when working inside a smaller tank.

The antenna's performances were experimentally characterized by connecting the antenna to the VNA and placing the antenna in the coupling medium. The measurement results of one antenna in the coupling medium are reported in Figure 5 as well, where a quite good agreement is achieved up to 2 GHz. The simulation and the measurement results well agree each other below 2 GHz, whereas a larger difference is observed above 2 GHz. This suggests that more accurate simulations would be required to better model the antenna behavior at higher frequencies. However, for the purposes which are aimed, such more refined modeling is not strictly required, as the in-silico validation of the MWI system for liver ablation [7] has demonstrated that the 0.5-1.5 GHz band is the suitable one to perform the imaging task. From the S-parameter measured in the coupling medium, a matching from 600 MHz to 3 GHz is obtained, with the possibility of working even at higher frequencies.

The E-field distribution calculated with the antenna placed inside the coupling medium is shown in Figure 6 for



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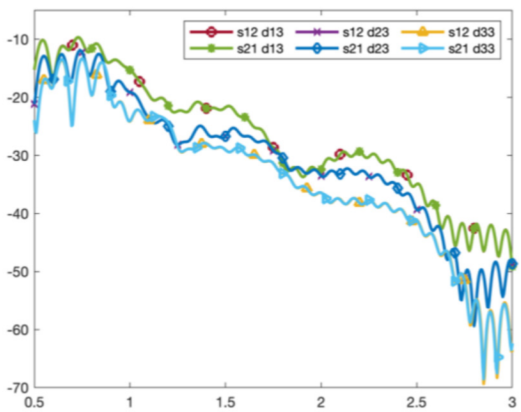


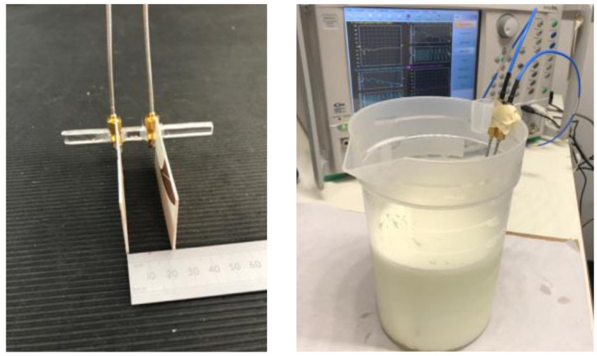
(b)

FIGURE 7. Simulation results of two slot-loaded antipodal Vivaldi antenna in array configuration: (a) s11, s22 parameters; (b) s12, s21 parameters. Different distances were considered between the two antennas, namely 13 mm (d13), 23 mm (d23), 33 mm (d33).

different frequencies. It can be seen that the E-field amplitude decreases as frequency increases. This is due to the fact that the coupling medium losses increase at higher frequencies.

In order to verify the antenna's performances in the array configuration, the antenna's matching was simulated when placing two antennas close to each other. Different distances between the antennas were characterized, i.e., 13 mm, 23 mm, and 33 mm. The antennas were all simulated inside tank C filled with the coupling medium. The simulation results are shown in Figure 7.

It can be seen from the figure that the S-parameters of the two slot-loaded antipodal Vivaldi antennas vary slightly as the distance between them changes. The antennas' s11, s22 show a better matching around 1 GHz when the distance is 33mm. This is because when placing two antennas further from each other, they are less likely be influenced by the mutual coupling effect. However, it can be noted a deeper resonance at about 600 MHz when the antennas are placed at 23 mm distance. Similarly, the s12, and s21 parameters of the antennas show a lower signal level when placing the antennas 33mm away from each other, but the data simulated at the other two distances are quite close.



(a) (b)

FIGURE 8. (a) antenna in the array configuration; (b) antenna measurement inside the coupling medium (ERMIAS Lab at University of Calabria).

for the experimental evaluation the distance of 23 mm was chosen as a trade-off between antenna performances and the possibility of placing more antenna elements in the array configuration. To characterize the antenna's matching, the two antennas were placed inside the coupling medium and connected to the VNA (Figure 8).

The simulated and measurement results of the antennas are shown in Figure 9. In particular, Figure 9 (a) shows the reflection coefficient of one antenna (s11) and of the two, closely located, antennas (s11, s22), while Figure 9 (b) reports the transmission coefficients (s12, s21) of the two antennas. Again, it can be seen that simulation and measurement results well agree each other from 0.5 to 2 GHz, while a discrepancy is observed above 2 GHz, for the reasons mentioned above.

The antenna matching at low frequencies, especially around 600 MHz, remains even with the presence of a nearby antenna. Additionally, the mutual coupling, represented by the s21 and s12 parameters, is well below −10 dB in the whole frequency band, with lower measured values than the simulated ones, probably due to the presence of losses in the coupling medium. From the figure it can be concluded that the slot-loaded Vivaldi antenna shows very good performances towards mutual coupling.

Table 6 shows the comparison between the antenna proposed in this work and other antennas design adopted in MWI medical applications. It is found that the proposed antenna offers the most compact aperture dimensions as compared to other configurations working with similar bandwidth. All the above features reveal that the antenna is suitable to be arranged into the array configuration needed by a microwave imaging device for monitoring liver ablation.

IV. CONCLUSION

This study reports the design, realization, and experimental assessment of the coupling medium and slot-loaded antipodal Vivaldi antenna to be adopted in a microwave

TABLE 6. Comparison among different antennas designed for MWI systems.

Ref	Antenna type	Bandwidth [GHz]	Dimensions [mm]	Applications	Coupling medium properties
This work	Vivaldi antenna	0.6-3	40×1.575×65	Liver ablation monitoring	At 1 GHz: $\varepsilon_r \cong 22.6$, σ=0.3 S/m
[6]	Vivaldi antenna	0.5-5	60×1.905×60	Liver ablation monitoring	At 1 GHz: $\varepsilon_r \cong 23$, σ=0.07 S/m
[10]	Patch antenna	0.8-1.2	50×50×70	Brain imaging	At 1 GHz: $\varepsilon_r \cong 20$, σ ≅ 0.2 S/m
[12]	Bowtie antenna	0.45-1.45	50×1.27×50	Breast imaging	At 0.5 GHz: $\varepsilon_r = 35$, σ=0.5 S/m
[13]	Horn antenna	1-11	25×20×13	Breast imaging	No coupling medium was used

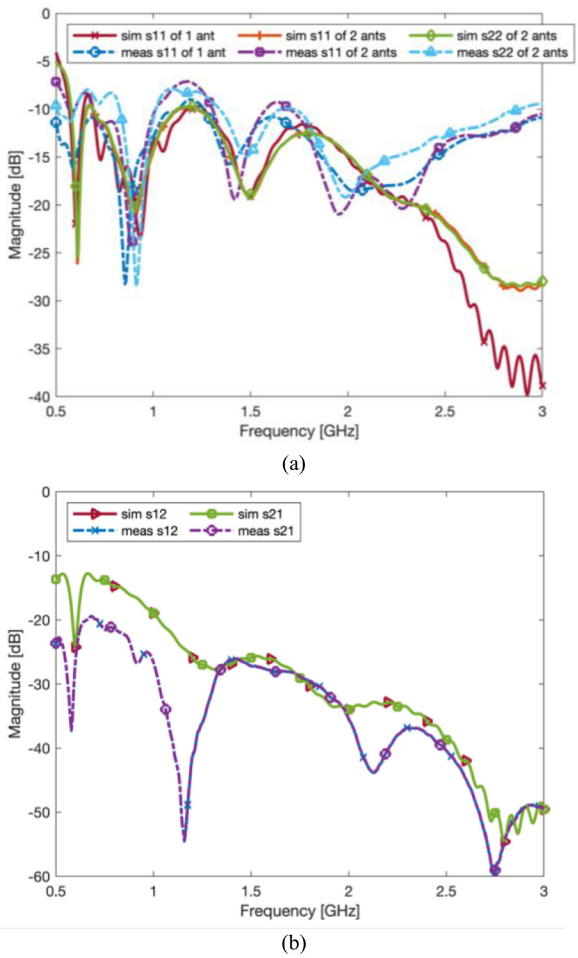


FIGURE 9. (a) Simulation and measurement s11 result for one antenna and two antennas, (b) Simulation and measurement s12, s21 of two antennas.

imaging system to monitor liver thermal ablation. The coupling medium was realized using low cost, easily procurable and usable materials, and proved stability of its dielectric properties on a 1-week time. The antenna was designed and characterized in a coupling medium specifically conceived for the system. The measured S-parameter of the single antenna well agrees with the simulation results, showing a matching from 600 MHz up to 3 GHz, with the possibility to work even at higher frequencies. The antenna's matching in the array configuration shows the slot-loaded design has good performance toward mutual coupling. A comparison of the antenna proposed in this work and configurations from other papers in the literature suggested that the proposed antenna has the most compact aperture dimension, and it is suitable to be arranged into the array configuration needed by a microwave imaging system for monitoring liver ablation.

The designed coupling material and antenna represent the basic elements of a microwave imaging system for monitoring microwave thermal ablation procedures. Accordingly, next steps will be the development of an experimental set-up to allow performing MWI experiments on an anthropomorphic liver phantom, as well as considering the patient position during the ablation treatment.

AUTHOR CONTRIBUTIONS

The paper is the result of a collaborative effort among the authors. More specifically, Study Design & Methodology: L.C., M.C.; antenna design, experimental validation, M. W, S. C, Data analysis: M. W.; Antenna Realization: S.C; Writing—original draft: M.W.; Writing—review & editing, S.C., R.S., M.C., and L.C.; Supervision: L.C., M.C.

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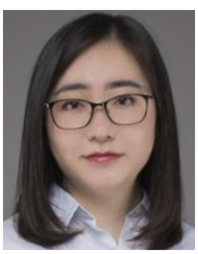

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