IEEE Open Journal of
Antennas and Propagation

Received 9 May 2021; revised 29 May 2021; accepted 3 June 2021. Date of publication 14 June 2021; date of current version 21 June 2021.

Digital Object Identifier 10.1109/OJAP.2021.3089028

A Compact Double-Ridged Horn Antenna for Ultra-Wide Band Microwave Imaging

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This paper is a substantial extension from presentation at the 2020 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting.

ABSTRACT In this paper, we introduce a novel and compact double-ridged horn (DRH) antenna for ultra-wide band microwave imaging. We first develop theoretical considerations useful to derive effective design guidelines and, thus, realizing the antenna model. Afterwards, an electromagnetic numerical solver is employed to study the conceived antenna both in free space and in the presence of a biological load; in both the simulation set-ups, excellent radiating performance are obtained, demonstrating the antenna robustness. Finally, a prototype is fabricated and experimentally measured to validate the final design. The proposed model presents overall dimensions that are 30% smaller with respect to traditional and commercially available DRH antennas (151 mm × 108 mm × 146.6 mm), retaining, at the same time, a significantly large operative band (VSWR <3 over the 1-9 GHz band). Among the broad class of possible applications, this frequency range is particularly suitable for biomedical devices, such as in microwave imaging, where reduced dimensions are fundamental in order to allow an easy integration within these systems. In addition, a safety assessment has been performed on the designed antenna, demonstrating that SAR is well below the regulating limits and it can be safely used in proximity of human operators.

INDEX TERMS Microwave imaging, breast cancer, double ridged horn, compact antenna, ultra-wide band.

I. INTRODUCTION

UNDOUBTDLEY, breast cancer is one of the leading cause of death for women and it has the highest incidence in the world [1]. Because of its high lethality, the most effective way to reduce the dangerous effects of this pathology consists in the early detection. Nowadays, extensive screening campaigns are conducted amongst women to spot the disease in its initial stage, when the traditional therapies, such as chemotherapy and radiotherapy, can be more effective. Actually, one of the most diffuse screening techniques is the x-ray mammography, which represents a very sensitive method although it is affected by a non-negligible number of false positives. Apart from this, the main drawback of mammography is the relatively high invasiveness, as the breast has to be rather compressed to achieve an image quality sufficient to derive diagnostic information; in addition, it uses ionizing radiations [2].

In this sense, Microwave Imaging (MWI) recently emerged as a very promising technique since it is based on the use of low-power and non-ionizing radiation, thus it is completely safe [3]–[7]. With particular reference to breast cancer detection, MWI does not involve any painful compression, since it is a contactless method; hence, it is significantly more comfortable than mammography and, moreover, it is remarkably less expensive [8]–[10]. These advantages make MWI a potentially perfect diagnostic tool to be integrated in the hospitals. Traditionally, MWI can be performed in two main modalities, i.e., by using a broadband signal (radar-based techniques) or by employing a single-frequency exciting pulse (common in 3D reconstruction imaging [7]).

The Ultra-Wide Band (UWB) MWI claims a long history as one of the most convenient way to detect inhomogeneities inside biological tissues. It basically involves illuminating the human district (as the breast) with short-time, low-power pulses of microwave energy using an opportunely designed transmitting antenna (or array of antennas). The signals scattered by the biological load are collected by the same transmitting antenna or by all the eventual radiating elements constituting the array and are processed to create spatial maps indicating the presence and location of biological inhomogeneities [11]. For such reason, this technique has an excellent capability to spot cancerous nodules [12]–[16].

Clearly, a key element in the design of MWI systems regards the choice of the type of antenna that illuminates tissues. Several antenna typologies have been proposed in the literature; for instance, dipole and monopole antennas, Vivaldi antennas, horn antennas and bow tie configurations [17]–[19]. Moreover, metamaterials and metasurfaces have also widely employed to enhance the performance of antennas, also for biomedical applications [20]–[24]. Each solution has its own advantages and drawbacks, thus the choice is mainly determined by the specific constraints of the experimental set-up. However, in general a wide operating bandwidth and unidirectional radiation are two essential requirements for MWI system in order to obtain high resolution images and eliminate effects of the surrounding environment [25]. In practice, these requirements can be translated into a suitable impedance matching, minimum signal distortion, and radiation pattern (and gain) stable in frequency.

Unfortunately, all of these features are challenging to be obtained with a small radiating element. Nonetheless, the available space in MWI biomedical applications, as breast cancer detection, is very limited; thus, keeping antenna size as compact as possible is extremely important. To achieve this goal, the present manuscript is devoted to the design and implementation of a compact transmitting antenna to be inserted in an MWI system for the detection of breast cancer. Double-ridged horn (DRH) antennas are one of the most suited typologies to be used in UWB MWI, thanks to their large bandwidth and appropriate radiation patterns. Presently, commercially available DRH antennas [26], [27] are too large for a proper integration in a typical MWI system. Thus, we propose a novel DRH antenna design able to achieve large bandwidth and optimal radiation patterns, suitable for MWI. The proposed antenna has been numerically realized starting from a theoretical analysis which allowed us to derive useful design guidelines. A prototype has been therefore fabricated to validate the theory and the simulations.

The paper is organized as follows; Section II presents the general theoretical aspects considered for the double-ridged antenna design, whereas in Section III the numerical model and the fabricated prototypes are shown. Section IV is devoted to discussing the results obtained from simulations and experimental measurements, in free space and in the presence of a biological load. Finally, Conclusion follows.

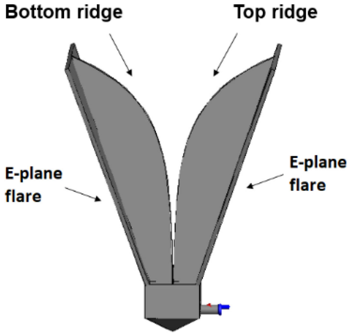


FIGURE 1. Schematic draw depicting the proposed double-ridged horn antenna: The main radiating components are highlighted.

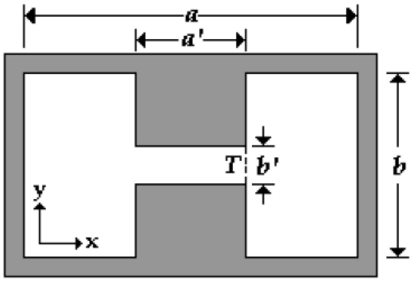
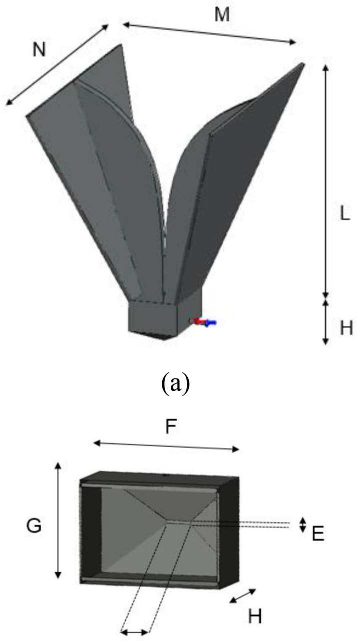


FIGURE 2. Proposed double-ridged horn antenna: The draw reports the main geometrical parameters of the cavity section.

II. THEORETICAL ASPECTS

The proposed antenna design (Fig. 1) has been realized starting from the typical structure of a traditional Double Ridged Horn, both in shape and size [28]. Since this paper is focused on MWI, it is worth noticing that an useful frequency range for breast cancer detection in MWI is represented by the band 1-9 GHz. This bandwidth was chosen as an acceptable compromise between a good penetration depth within biological tissues and a good spatial resolution; indeed, the penetration depth is guaranteed by the lower frequency range, whereas the higher frequencies can achieve the required spatial resolution. From a theoretical point of view, it has been shown in the literature that MWI for breast cancer reaches a limit resolution of $\lambda/4$ [29]. Hence, all the design choices are directed in order to obtain the satisfaction of these main requirements.

Inspired by such observations, one of the preliminary modifications we introduced was the elimination of the rectangular flares corresponding to the H-plane (Fig. 1). This simple design choice leads to a lower frequency value of the antenna operative band. It is straightforward to understand that this is the most critical aspect, because maintaining compact dimensions trying to achieve a lower operative frequency can be extremely challenging. Indeed, the antenna structure is becoming smaller and smaller



(a)

(b)

FIGURE 3. **CAD model of the designed compact DRH antenna: (a) Entire CAD model; (b) antenna cavity. The size corresponding to the labels are reported in Table 1.**

with respect to the wavelength and, usually, the radiating efficiency drops.

Another fundamental design expedient regards the feeding line. Supposing that a standard 50-Ω coaxial cable is used to connect the signal generator to the antenna, then its inner conductor was secured to the antenna through a hole in the top and bottom ridges forming a short circuit between these two elements [30], [31]. This expedient retains several advantages. Firstly, the electrical contact is mechanically more robust; moreover, the correct impedance matching is easier to be obtained and, finally, a strong suppression of higher order modes can be accomplished.

In addition, also the cavity structure was redesigned with respect to a standard double-ridged horn antenna, as explained in [32]. In particular, an optimal choice of the size and the shape of the pyramidal cavity of the waveguide is fundamental for a low Voltage Standing Wave Ratio (VSWR) over a large bandwidth and for a radiation pattern suitable for the required application (i.e., with a relatively good directivity) [30], [32], [33]. In Fig. 2 a section of the waveguide that is formed within the cavity is depicted. Assuming that the waveguide has external dimensions a and b, whereas with a' we indicate the ridges thickness and with b' the ridges reciprocal distance, then the antenna cut-off frequency for the fundamental mode can be expressed as follows [34]:

$$\frac{Y_{02}}{Y_{01}}\tan\frac{\pi}{\lambda_c}a' + \frac{B}{Y_{01}} - \cot\frac{\pi}{\lambda_c}\left(a - a'\right) = 0 \qquad (1)$$

where $Y_{01} = \sqrt{\varepsilon/\mu}(1/b)$, $Y_{02} = \sqrt{\varepsilon/\mu}(1/b')$, ε and μ are the medium permittivity and permeability, $\alpha = b/b'$, and,

TABLE 1. **Geometrical parameters of the proposed DRH antenna.**

Label	*Description*	*Dimension (mm)*
D	*Bottom Waveguide length*	6
E	*Bottom Waveguide width*	1.2
F	*Waveguide width*	42
G	*Waveguide length*	32
H	*Cavity height*	28
L	*DRH Antenna height*	120
M	*DRH Antenna length*	151
N	*DRH Antenna width*	108

finally, the susceptance is given by:

$$ {}^{B}\!/_{Y_{01}} = \frac{2b}{\lambda_c}\left[\frac{\alpha^2+1}{\alpha}\cosh^{-1}\left(\frac{1+\alpha^2}{1-\alpha^2}\right) - 2\ln\left(\frac{4\alpha}{1-\alpha^2}\right)\right] \qquad (2)$$

Finally, we note that the ridges profile is another significant parameter that heavily affects the antenna performance. In particular, we decided to adopt an exponential profile; in this way, an excellent impedance matching between the waveguide section and the free space can be obtained. It is also worth noticing that a linear part in the ridges superimposed to the exponential one can lead to a significant VSWR improvement at the lower frequencies, while the remaining operative band remains unaltered. As also evident from Fig. 1, the linear part of the profile starts in the correspondence of the feeding line, whereas the exponential part is present towards the end of the cavity box, as in [35]. Analytically, the ridges exponential profile can be written as follows:

$$S(t) = ae^{bt} \qquad (3)$$

in which $0 \leq t \leq L$ and b is calculated as in (2):

$$b = \frac{1}{L}\ln\left[\frac{z(L)}{z(0)}\right] \qquad (4)$$

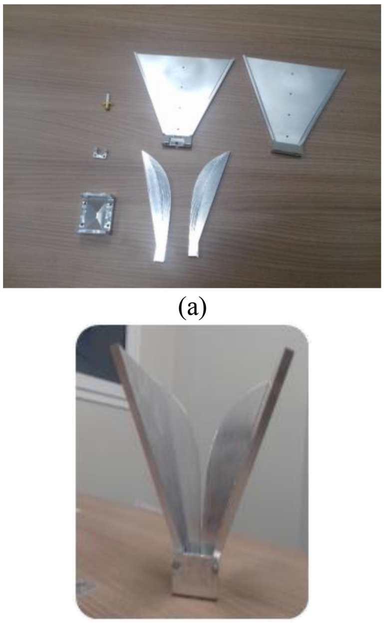
In particular, L is the axial length of the antenna, z the distance from the axis of symmetry, t is the exponential length of the profile of the ridge, where the starting point corresponds to the end of the linear profile and the end point of t corresponds to the depth of the horn antenna.

III. ANTENNA MODELING

A. NUMERICAL DESIGN

Following the guidelines highlighted in the previous section, we realized the antenna design by employing a numerical electromagnetic solver; in particular, we selected a Method of Moments CAD environment (Feko Suite, Altair, MI, USA).

In Fig. 3 we reported two views of the realized compact DRH antenna, with a label for each geometrical detail. Along with the design guidelines, an optimization procedure was also performed to find the best values that allow to cover



(a)

(b)

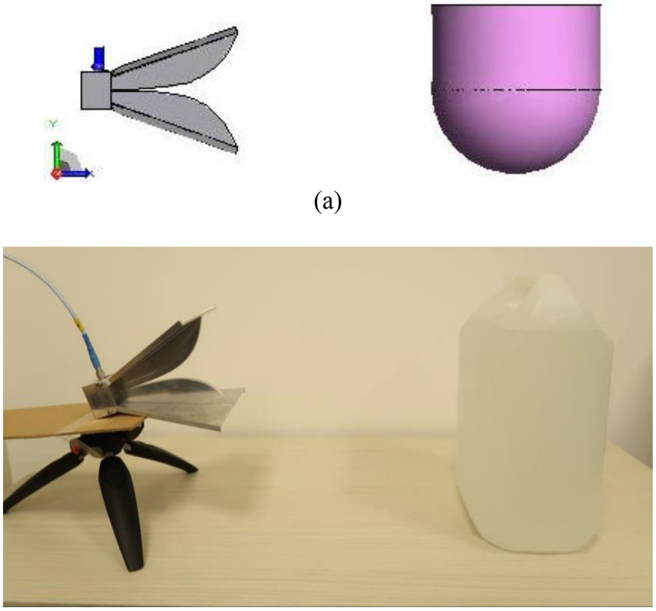
FIGURE 4. **Fabricated prototype: (a) Designed DRH antenna pieces; (b) assembled DRH antenna. The antenna is made of aluminum and realized by milling technique.**

the desired bandwidth (1-9 GHz) with the appropriate radiation capabilities for MWI applications. The optimization procedure, along with the design guidelines presented in the previous section, has been conducted in both conditions, i.e., antenna operating in free space and antenna operating in the presence of the biological load. Table 1 shows the values for each geometrical parameter considered in the procedure. As it will be better discussed later, it must be noticed that the proposed design is extremely compact, especially if we consider the lower frequency range (1 GHz); indeed, the major antenna dimension (labeled M) is only 151 mm.

B. FABRICATED PROTOTYPE

Beside the numerical design, we also fabricated a prototype of the proposed antenna. In particular, we selected aluminum as material; this material represents an excellent compromise between cost, machinability and light weight. Specifically, the reduced weight is an important constraint in order to allow its effective usage inside a MWI system. The antenna components (Fig. 4 (a)) have been realized by milling technique, which allowed a very strict tolerance (about 0.5 mm). In addition, an opportune mechanical and electromagnetic combined study has been conducted to provide screw holes for the assembly without damaging the radiating performance.

Finally, the antenna was assembled, as reported in Fig. 4(b). As evident, the structure is mechanically stable thanks to the fabricating technique, thus reproducibility and cost-effectiveness are guaranteed.



(a)

(b)

FIGURE 5. **The proposed compact DRH antenna was evaluated also in the presence of a phantom which emulates a breast (a). For the experiment, a saline solution was used to emulate the tissue (b).**

IV. RESULTS AND DISCUSSIONS

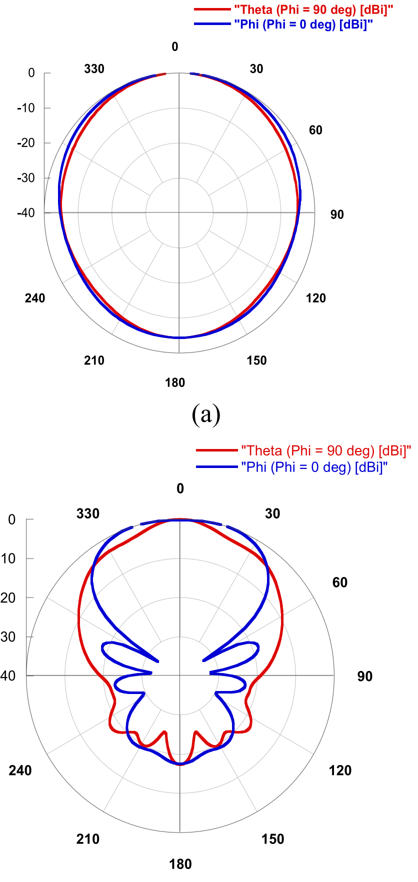
In this section, we present the results obtained from numerical simulations and experimental measurements. In the specific, the antenna radiating performance are evaluated: not only the VSWR and the radiation patterns, but also the antenna gain and the near field directivity (NFD) are reported. The evaluations are carried out both in free space and in the presence of a biological load.

As it will be better described in the following, we adopted in the numerical simulations a homogeneous breast phantom, as depicted in Fig. 5(a). The phantom is characterized by a dielectric permittivity of $\varepsilon_r = 48$ and a conductivity of $\sigma = 0.4$ (S/m) at 5 GHz (center frequency of the considered span). Its size is within the range of a typical humane female breast with a diameter of 160 mm and it is placed 320 mm away from the radiating element. In the experimental measurements, the phantom was realized with a saline solution which presents the same dielectric properties of the simulations.

Moreover, since the envisaged antenna application involves human subjects, a study on the electromagnetic safety is conducted, and the Specific Absorption Rate levels produced by the designed antenna within the adopted human breast phantom are assessed.

A. ANTENNA RADIATING PROPERTIES

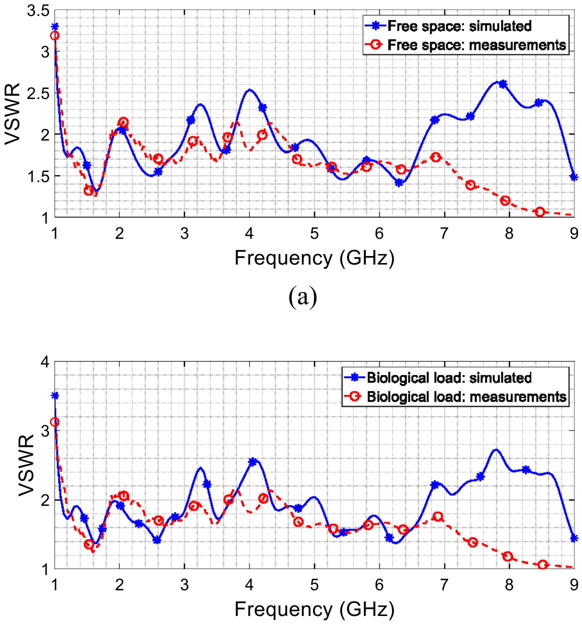
As the first step, the radiation patterns have been evaluated with the numerical solver FEKO. In Fig. 6 the radiation pattern on the two principal planes (i.e., E and H plane) are reported at two frequencies (1 and 8 GHz). These two values are representative of the desired working bandwidth boundaries. As evident from the graphs, the half-power beamwidth



(a)

(b)

FIGURE 6. **Simulated Radiation patterns of the novel compact Double Ridged Horn antenna: At 1 GHz (a) and 8 GHz (b).**



(a)

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FIGURE 7. **Comparison between simulated (blue full line) and measured (red dashed line) VSWR from 1 to 9 GHz: (a) free space and (b) in presence of the biological phantom.**

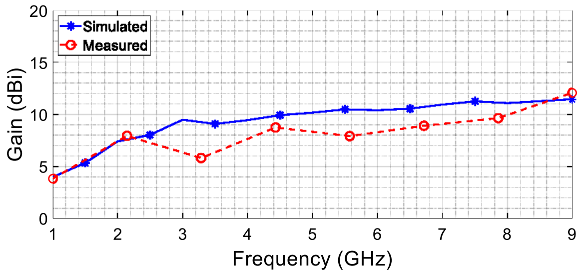

FIGURE 8. **Comparison between simulated (blue full line) and measured (red dashed line) antenna gain from 1 to 9 GHz.**

is able to uniformly illuminate the breast over the entire frequency band; this guarantees that the novel Double Ridged Horn antenna has optimal performance with respect to MWI breast cancer detection.

Further, the VSWR parameter was evaluated: we compared simulated and measured results in two conditions, i.e., compact DRH antenna in free space and in the presence of the biological load (as represented in Fig. 5). For the measurements, we used a standard Vector Network Analyzer (FieldFox N9938A, Keysight, Santa Rosa, CA, USA). It must be pointed out that numerical and measured results are in excellent agreement, in both the configurations, validating the overall design process. In particular, considering a VSWR less than 3 as the useful operative threshold, the entire desired band from 1 to 9 GHz is covered, both in free space conditions and in the presence of biological tissue (Fig. 7). The latter aspect is very important, because it confirms that the antenna achieves a good impedance matching even if the biological material is positioned within the Fresnel zone of the radiated field. Interestingly, at the higher frequencies, the measurements performed over the fabricated prototype show even a better impedance matching than simulations; this was likely due to the slight positioning and modeling differences of the antenna feed point between simulations and experimental measurements.

In addition, the simulated and measured gain is reported in Fig. 8. As evident, the agreement between numerical evaluations and experimental measurements is good and the excellent antenna performance can be highlighted.

Finally, in order to investigate the radiating properties of the antenna for imaging purposes, the near-field directivity (NFD) parameter has been considered. Hence, following the evaluation methodology explained in [36], we calculated the NFD for the proposed compact DRH antenna, showing the obtained results in Fig. 9. As evident, the developed design shows an excellent NFD parameter, especially at the higher frequency range.

As anticipated in the previous sections, it is important highlighting that the overall dimensions and weight of the designed and fabricated DRH antenna are significantly smaller than commercially available DRH antennas. In particular, we achieved a 30% size reduction with respect

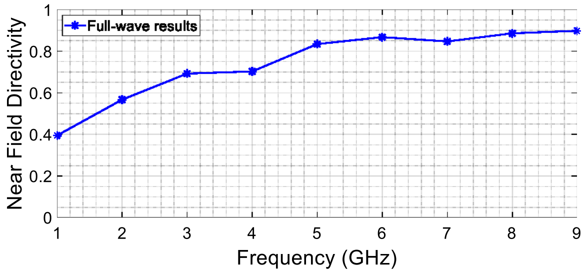

FIGURE 9. Near-field directivity evaluated following the method described in [36]; as evident, the designed horn antenna presents an excellent NFD parameter.

TABLE 2. Comparison between the proposed horn design and the state-of-the-art.

Antenna	*Size (mm)*	*Bandwidth (GHz)*	*Weight (kg)*
Design in [31]	240×137×212	0.8-20	N.A.
Design in [34]	240×138×152.4	1-14	*Simulated*
Design in [37]	184×126×112	1-18	*Simulated*
Commercial version [26]	243×154×200	1-18	0.8
Proposed Design	151×108×146.6	1-9	0.3

to [26], and this result is remarkable because not only a very large bandwidth is retained but also because the lower frequencies are preserved (Table 2). This is extremely challenging because the electrical length of the antenna is smaller and the radiation efficiency usually drops. In this sense, to the best of our knowledge, our proposal is novel and it can be usefully applied in all the applications requiring compact dimensions and ultra-wide band behavior.

B. SPECIFIC ABSORPTION RATE ASSESSMENT

Since the envisaged application for the designed compact DRH antenna is biomedical, a fundamental analysis must be also conducted to assess the electromagnetic safety. Traditionally, international guidelines emanated by the ICNIRP organization are the most adopted and recognized norms [38]. Therein, the limit for whole-body exposition is set in 0.08 W/kg, as for the general public. However, in particular situation, for instance for workers or special medical procedures (like MRI), these limits can be raised but under a strict control [39], [40].

In order to achieve a realistic evaluation relative to our case, we considered the maximum input power that can be used for the proposed DRH antenna, i.e., 10 mW. This power represents the typical value for MWI breast cancer detection. Moreover, we also selected as the test-frequency the value of 6.2 GHz, which corresponds to the point of best impedance matching point of the antenna (according to the numerical results, Fig. 7); in this way, the worst case for the SAR evaluation has been selected, where the greatest part of the power is flowing into the antenna and it is then radiated towards the biological tissues.

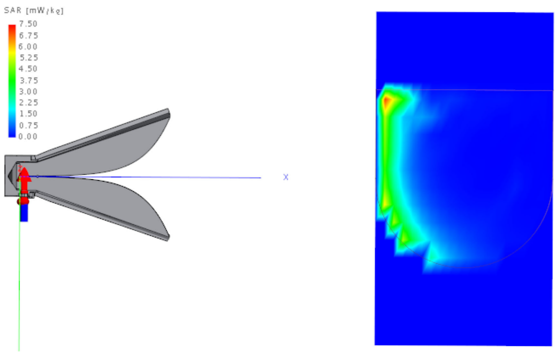

FIGURE 10. Specific Absorption Rate evaluation: We considered the antenna fed at the maximum power allowed for MWI applications (10 mW) and at the frequency of 6.2 GHz, where the best impedance matching is observed.

Fig. 10 reports the obtained local SAR distribution within the breast phantom; as evident, the maximum observed value is 7.5 mW/kg, well below the limits specified in the norms. This preliminary investigation demonstrated the overall safety of the device under evaluation from an electromagnetic point of view; indeed, in order to approach the SAR limits, unrealistic input power levels for MWI applications should be used (at least ten times higher).

V. CONCLUSION

In this paper, a novel Double-Ridged Horn antenna design suitable for microwave ultra-wide band breast cancer detection is presented. The proposed antenna is significantly more compact, resulting in a 30% size reduction with respect to commercially available DRH antennas. Nonetheless, it maintains excellent radiating performance, especially at the lower frequency range (1-9 GHz). We first conducted a theoretical analysis to derive useful observations and guidelines to achieve the desired design. Then, we simulated the antenna through a commercial numerical solver, both in free space and in the presence of a biological breast phantom. Furthermore, we fabricated a prototype of the model, obtaining excellent agreement with simulations, in both the free space and biologically-loaded conditions. Finally, the obtained antenna has also been checked about the electromagnetic safety level; the numerical simulations that we conducted demonstrated that the SAR levels produced by the compact DRH antenna are well below the international limits. To the best of our knowledge, this is the most compact ultra-wide band DRH antenna ever presented; the reduced size, along with excellent radiating performance, make the antenna a good candidate to be employed in Microwave Imaging. Further developments will be directed to include the antenna within a real Microwave Imaging device and to conduct future clinical tests.

ACKNOWLEDGMENT

The authors would like to thank Dr. Gianluigi Tiberi for the stimulating and fundamental discussions. Moreover, the authors are grateful to Dr. Giacomo Berti for the precious

support in the mechanical optimization and fabrication of the antenna.

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