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Compact Dual-Polarized Quad-Ridged UWB Horn Antenna Design for Breast Imaging

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Abstract—A compact dual-polarization, ultra-wideband quad-ridged horn antenna has been proposed for breast imaging. CST Microwave Studio Simulation has been used to design the horn antenna. The antenna size was reduced, and impedance matching was achieved by a modest change in the dielectric constant of the matching liquid and by the introduction of four semi-elliptical structure at the flared ridges. To test the polarization isolation, many field probes were distributed at different positions in front of the antenna. The probes have been set to measure both vertical and horizontal electric field components at each location. Results show that adding elliptical parts can provide impedance matching over the whole frequency band of the antenna. Measurements show high isolation between the transmitted vertical and horizontal electric fields. Almost 40 dB polarization isolation exists at boresight of the antenna over the entire frequency band. This characteristic is central to polarimetric radar work. Effective gain and ports isolation were obtained.

1. INTRODUCTION

The ultra-wideband (UWB) microwave imaging (MI) technique has attracted the attention of many researchers since the Federal Communications Commission (FCC) has allocated the frequency range between 3.1 and 10.6 GHz for UWB emissions in 2002 [1]. One important application of MI is breast cancer detection in women, where an early detection of breast cancer translates to a better chance of healing and survivability [2, 3].

The two well-known mechanisms of breast MI techniques are microwave tomography and radar-based imaging. Microwave tomography can be considered as a narrowband system. On the other hand, radar-based imaging needs large bandwidth [2]. Breast cancer imaging techniques require very compact antennas to be accommodated in an array of elements around the breast. Therefore, for an antenna to be suitable for radar breast imaging, it has to be compact with an UWB signal to produce high-resolution images.

Different types of antennas have been proposed for breast imaging. For travelling wave antennas, Vivaldi antennas and horn antennas are widely used [3–6]. For the same breast phantoms, it is found that breast images formed from datasets collected by horn antenna have lower noise level and higher contrast than the images with datasets recorded using Vivaldi antenna [7]. Horn antennas have preferable features such as versatility, simplicity and good radiation performance, so they are commonly seen in microwave measurement, radar, and detection systems [8].

The bandwidth of the conventional horn antenna is limited. To broaden the band of the horn antenna, ridges in the waveguide transition portion and in the flare region are inserted. Inserting ridges forces the cutoff frequency of the TE11 mode to be close to the TE10 mode which results in a bandwidth increment between the TE10 and TE20L modes [9, 10].

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Several double-ridged horn antennas (DRHAs) have been proposed for breast imaging. In 2003, a pyramidal-horn antenna with a single ridge and a curved launching plane was designed [11]. A novel UWB TEM horn antenna enclosed in a dielectric medium was proposed in [12]. A wideband DRHA is presented in [4], and the horn is loaded with distilled water and immersed in coupling liquids to reduce the size. Other designs of double-ridge horn antennas are proposed in [3] and [7]. All these horn antennas serve as single-polarized elements.

A dual-polarization system usually provides more information than a system with a single-polarization antenna [13]. Radar systems often use dual polarizations over an UWB range of frequency [10]. In [14], Hagness et al. investigated breast reflections using dual-polarization technique. Undesirable backscatter coming from planar surfaces such as the chest wall is significantly reduced by using dual-polarization approach. Thus, the tumor adjacent to the chest wall can be detected more easily. The results in [15] show the importance of collecting data at all polarizations. Practically, the orientation of a breast tumor is unknown. The likelihood of using a polarization parallel to the tumor's main axis is increased by rotating the dual-polarized antenna. As a result, the percentage of correct identifications of breast tumors increases.

A dual-polarization horn antenna can be obtained by loading quad ridges in a typical horn antenna [13]. A quad-ridged horn antenna (QRHA) can transmit and receive vertically and horizontally polarized signals separately [10]. This feature is very important in tumor detection [14].

In 2005, Shen and Feng designed a QRHA in [8], but their antenna was too big for breast imaging, as well as some latter designs reported in [9, 13] and [16]. While the antenna in [10] has a smaller size than aforementioned QRHA designs, it is still large for breast imaging. In addition, the frequency band is from 8 to 18 GHz with a VSWR ≤ 2.6, not 2.

To the best of our knowledge, only one publication has reported the design of quad-ridged dual-polarized horn antennas for breast imaging [17]. This research compares the performances of the DRHA and QRHA in tumor detection. However, the reflection coefficient of the QRHA in this research has a value of over -10 dB in many frequency ranges in the 3 to 10 GHz band.

In this paper, we propose a modified version of a QRHA for dual-polarization breast imaging. Novel semi-elliptical segments are introduced at the end of the ridges to match the antenna with the coupling liquid over all the antenna frequency band. The designed antenna shows good performance in term of return loss, ports isolation, and gain over ultra-wideband frequency. It also shows high polarization isolation between the two linearly polarized signals. The structure of the remaining of this paper is as follows. Section 2 details the design of the antenna. In Section 3, numerical and measured results are presented. Finally, conclusion is provided in Section 4.

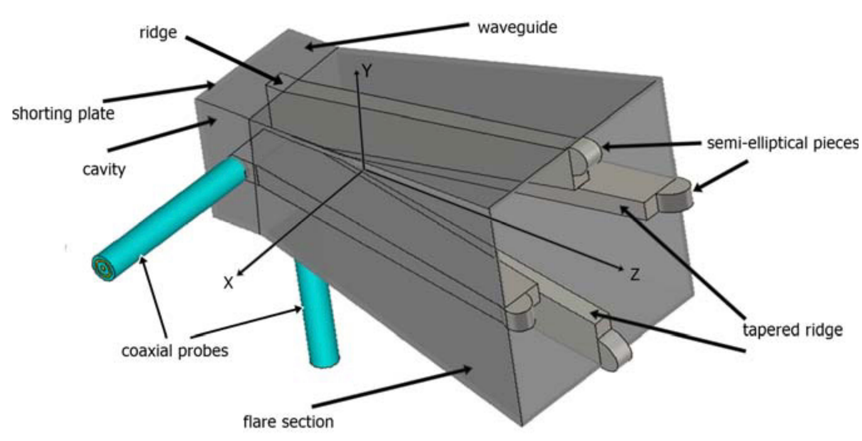


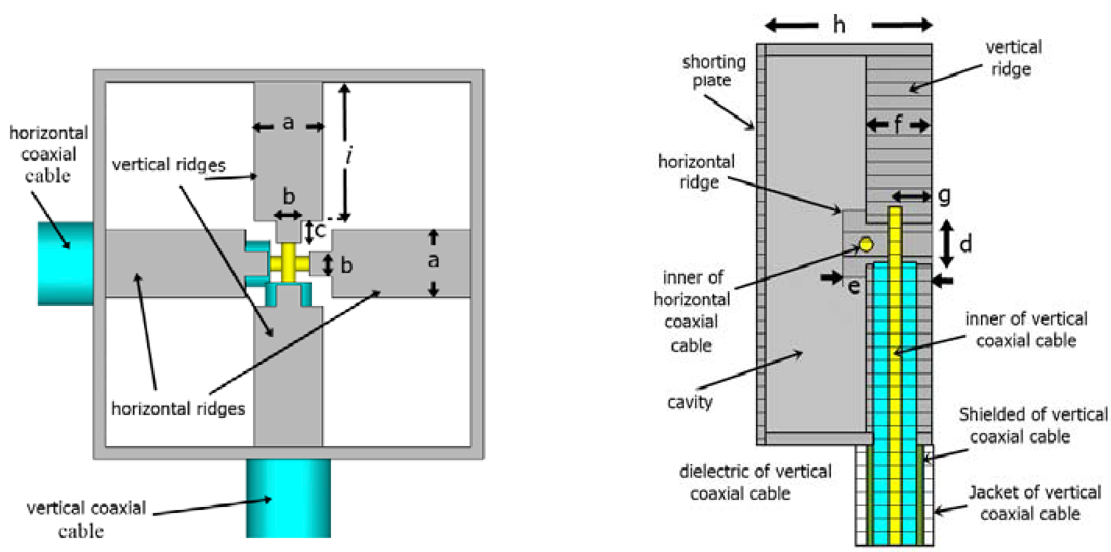
Figure 1. Geometry of the proposed antenna.

2. ANTENNA DESIGN

Figure 1 shows the configuration of the proposed QRHA. The industry standard simulation suite, CST Microwave Studio, has been used to design and analyze the antenna. The designed QRHA can be divided into two sections: a quad-ridged waveguide transition with a cavity at the back. The second section is the flare part of the horn antenna where the tapered quad-ridges are fixed. For impedance matching, the antenna is immersed in a coupling liquid. The suitable dielectric constant of the coupling liquid is found to be from 4 to 4.9, and $\varepsilon_r = 4.7$ is chosen for conducted tests. Many materials, especially alcohols, have dielectric constant between 4 and 4.9 in the GHz frequencies. For example, isopropyl alcohol has dielectric constant more than 4 over the entire antenna band [18]. The dielectric constant of alcohol can be increased and adjusted also by adding some water.

2.1. Quad-Ridged Waveguide Transition Design

The waveguide of the horn antenna consists of two parts: a square quad-ridged waveguide and a small rectangular cavity, described earlier, shorted by a plate at the end of the waveguide. The quad-ridged waveguide transition geometry is shown in Fig. 2, and the dimensions are described in Table 1. The antenna is fed through the quad ridges by two coaxial cables, one for vertical polarization (port 1) and the other for horizontal polarization (port 2). The waveguide transition length is 5.8 mm with aperture of 12.48 mm × 12.48 mm.



(a) (b)

Figure 2. Quad-ridged waveguide transition geometry. (a) Front side and (b) profile of side plane.

Table 1. Parameters of quad-ridged waveguide transition.

Parameter	a	b	c	d	e	f	g	h	i
Length (mm)	2.22	0.8	0.72	1.36	3.1	2.3	1.3	5.8	4.84

In order to avoid electrical contact, the dielectric layer, which surrounds the inner conductor of the coaxial cable, is inserted with the inner conductor through the lower and left ridges as shown in Fig. 2. The inner conductors are extended to the upper and right ridges while the outer shields of the coaxial cables are connected to the lower and left ridges.

The horizontal ridges (parameter e) are slightly longer than the vertical ones (f) inside the waveguide transition. This configuration allows for inserting the inner conductor of the horizontal coaxial cable. The distance between the centers of the inner conductors of the vertical and horizontal coaxial cables is 1 mm. To match the small dimensions RG174 type 50 Ω coaxial cable is chosen and simulated through CST Microwave Studio.

To obtain a short distance between the opposite two ridges at the feed point, all the ridges are notched as shown in Fig. 2(a). This distance (d) is optimized through CST Microwave Studio to obtain 50 Ω impedance at the feed point to match the coaxial cable impedance. The designed antenna has a simple rectangular cavity which is obtained by shorting the waveguide by a square plate at the back. Closing the waveguide from the back reduces the return loss and directs the radiation in the forward direction.

2.2. Horn Flared Section Design

The formation of the flared pyramidal part is depicted in Fig. 3, and the dimensions are listed in Table 2. The proposed antenna has a very compacted square aperture with a 23.6 mm side length. For such a small antenna design, it is hard to get impedance matching over the whole frequency band of the antenna. Some frequencies usually have VSWR values more than 2 which is the threshold value for impedance matching evaluation. This problem has been noticed in most of the designs referenced in the literature review even though these designs are larger than our proposed antenna.

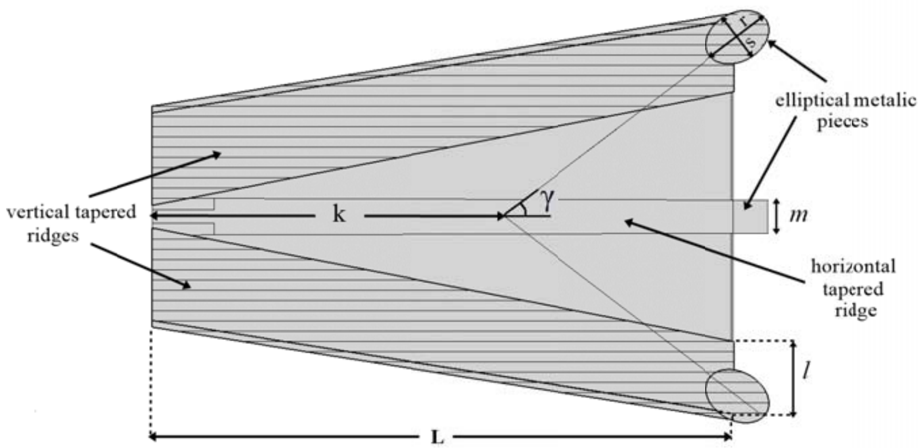


Figure 3. Cutting side plane of flared section.

Table 2. Parameters of flared section.

Parameter	k	l	m	r	s	L
Length (mm)	21.2	4.3	2	4	2.9	35

The impedance of the coupling liquid is found to be 173.897 Ω by using Equation (1)

$$Z_{\text{Castor}} = \sqrt{\frac{\mu_o}{\varepsilon_o \varepsilon_r}} \tag{1}$$

where $\varepsilon_r = 4.7$, the horn ridges should provide smooth transition from the impedance at feed point which is 50 Ω to the impedance of the coupling liquid (Z_{Castor}). For our antenna, four identical ridges are designed to be linearly tapered using the following equation:

$$y(x) = \frac{341}{1750}x + 0.68, \quad 0 \le x \le L \tag{2}$$

where L is the overall length of the flare section of the horn.

The antenna was first designed without the elliptical parts at the end of the tapered ridges. As expected, the ridges do not achieve impedance matching at some frequencies. Adding aslant metallic oval at the end of each tapered ridge can solve this problem. The ellipse shape provides a longer path for the surface current on the ridge. As a result, the new configuration helps the ridge in signal transmission in all of the frequency band with less returned signal. In other words, the ovals provide smooth transition of the wave traveling between the ridges in the flare section of horn antenna to the wave radiated in the coupling liquid. The tilt angle (γ) in Fig. 3 has a value of 51°. The vertical and horizontal diameters of the ovals which are parameters (s and r), respectively, are optimized to get the best result.

3. TESTS AND RESULTS

In all conducted simulation tests, the proposed QRHA is immersed in the coupling liquid. To check the antenna bandwidth, VSWR is considered. The antenna can properly transmit and receive signal when SWR is ≤ 2 or the reflection coefficient ≤ -10 dB. The VSWR values of the proposed antenna without the four elliptical pieces for the two ports are tested and plotted in Fig. 4. It is clear that the designed antenna has a frequency band from almost 3.8 GHz to 10.6 GHz for the two ports. However, the antenna failed in matching in many frequencies inside the band, and many values of VSWR are more than 2.

The VSWR test is repeated after introducing the four metallic ovals, and the result is shown in Fig. 5. Obvious improvement has been obtained in the antenna bandwidth by inserting the elliptical parts. All VSWR values have become less than 2 in the antenna bandwidth. From Fig. 5, the final design of the proposed antenna covers the frequency band (from 3.72 GHz to 10.52 GHz) for port 1 and (from 3.63 GHz to 10.74 GHz) for port 2. For our final design, the isolation between the two coaxial ports is depicted in Fig. 6. The two curves are identical with isolation better than 39.2 dB over the entire frequency band.

The gain of the simulated antenna is shown in Fig. 7 for the two ports: port 1 transmits and receives vertically polarized signals and port 2 the horizontally polarized signals. Gain is plotted over

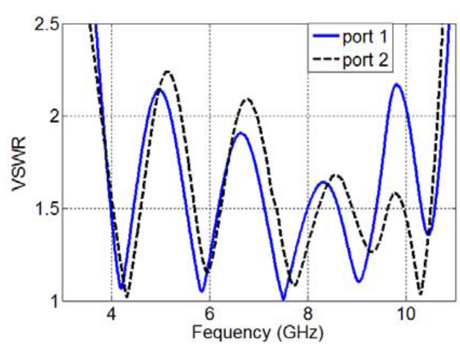


Figure 4. VSWR of the proposed antenna without the elliptical parts.

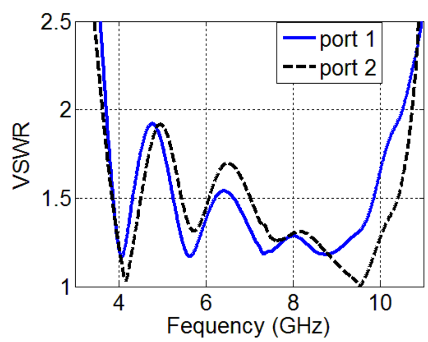


Figure 5. VSWR of the proposed antenna with the elliptical parts.

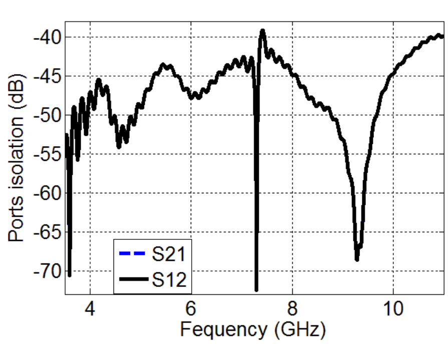


Figure 6. Isolation between the two ports.

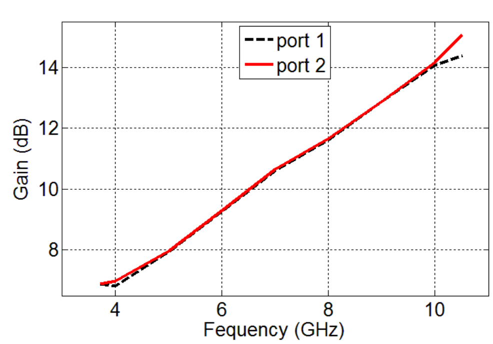


Figure 7. Gain of the proposed antenna.

the entire antenna frequency bandwidth. It is clear that both gains are similar to each other over most of the band with relatively high values which is required for radar based breast imaging technique. The minimum gain is 6.88 dB while the maximum is 14.9 dB.

The most important aim for which the antenna has been designed is providing dual polarizations with high isolation between the vertical and horizontal polarizations. A polarization isolation test is conducted by placing several field probes in two different locations and orientations on the boresight line of the antenna. The field probes are arranged as shown in Fig. 8. At each location, a pair of probes has been placed, a vertical probe to observe the vertically polarized radiated field and a horizontal one to observe the horizontally polarized transmitted field. First, the antenna sends an UWB signal from port 1 which corresponds to the vertical polarization. The electric field is recorded at all vertical and horizontal probes. During this time, port 2 which corresponds to horizontal polarization is turned off. Then port 1 is turned off, and port 2 radiates an UWB signal to be captured by the probes.

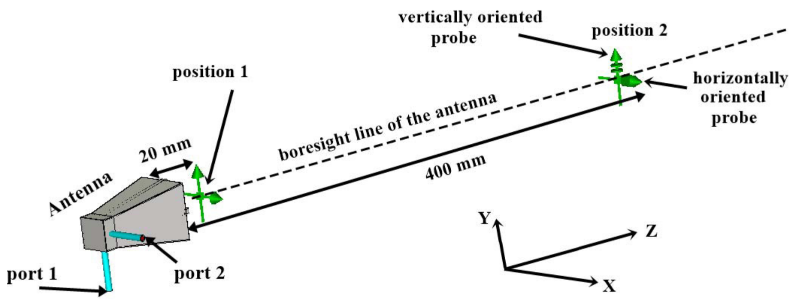


Figure 8. Distribution of field probes and horn antenna for polarization test.

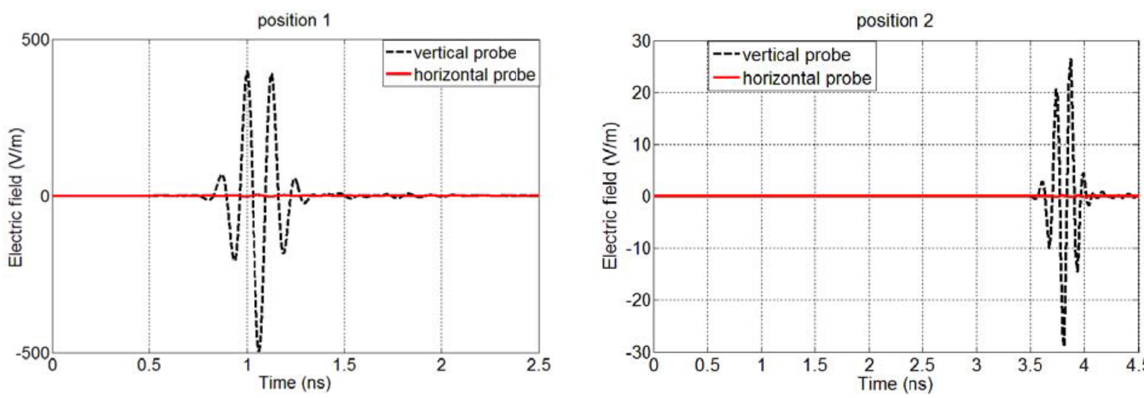


Figure 9. Observed electric fields by vertical and horizontal probes in time domain from port 1 radiation.

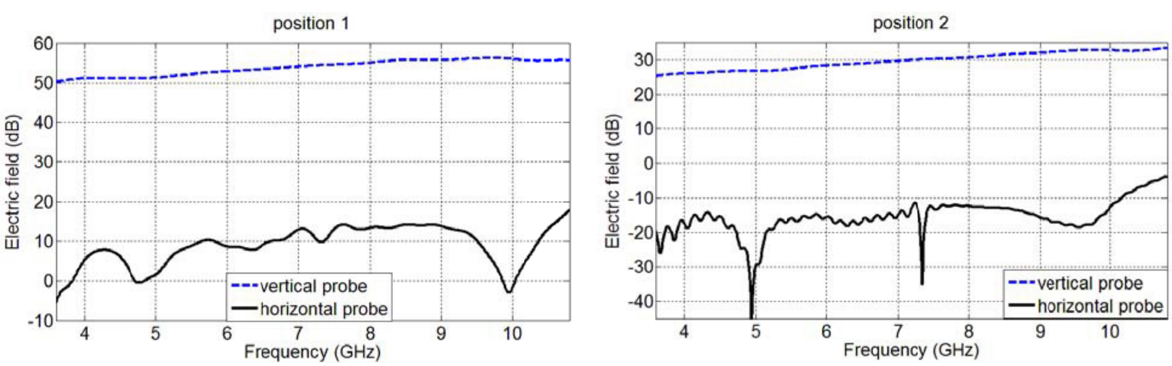


Figure 10. Observed electric fields by vertical and horizontal probes in frequency domain from port 1 radiation.

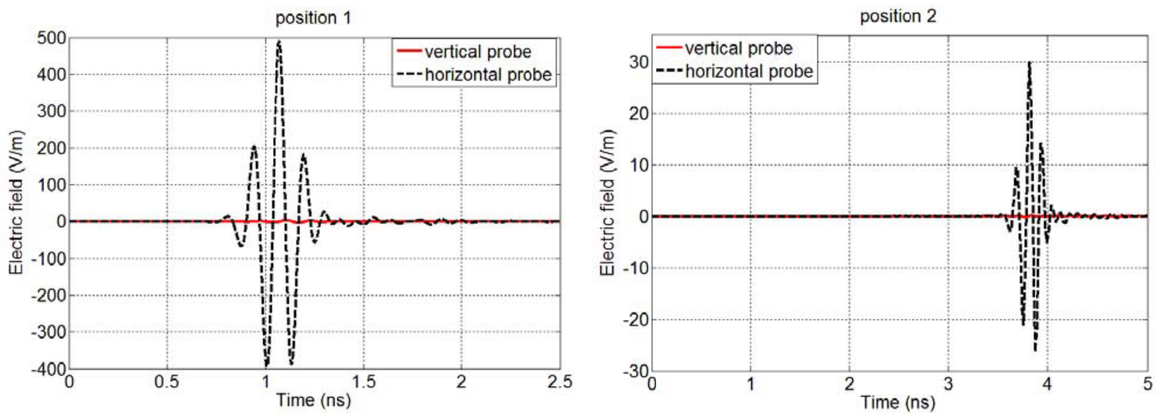


Figure 11. Observed electric fields by vertical and horizontal probes in time domain from port 2 radiation.

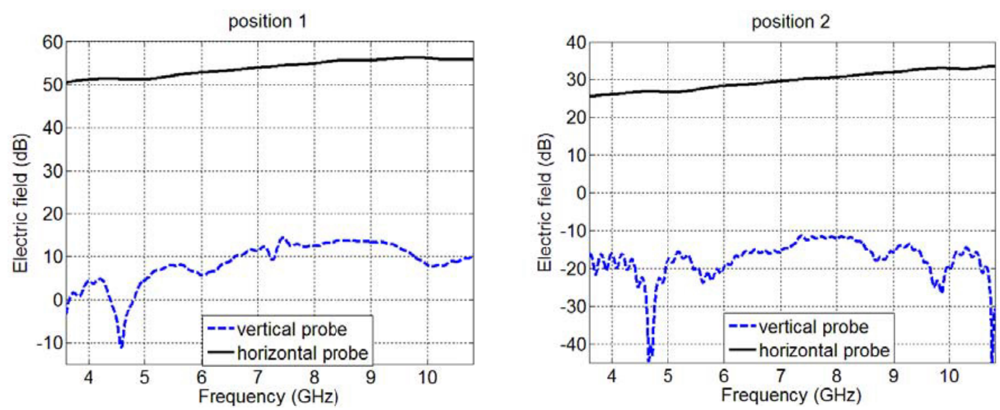


Figure 12. Observed electric fields by vertical and horizontal probes in frequency domain from port 2 radiation.

In position 1, the first probe pair is located to measure the electric field at 2 cm from the antenna. Position 2 is used for far-field measurement on the boresight line of the antenna at 40 cm. In step one, port 1 is on, and port 2 is off. The time-domain electric fields captured from port 1 in positions 1 and 2 are depicted in Fig. 9. The horizontal probe receives almost zero electric field compared to vertical probe signal. The observed electric fields in the frequency domain for this case are depicted in Fig. 10. Very high polarization isolation is shown in both field probes positions. The separation between the vertical and horizontal polarizations is almost 40 dB over the whole antenna band. For step two, port 1 is turned off, and port 2 is used for radiation. The time and frequency domains of the captured electric field are depicted in Figs. 11 and 12, respectively. Now, the horizontal signal is dominant with a difference of 40 dB as well.

4. CONCLUSION

A quad-ridged dual-polarization horn antenna has been proposed for polarimetric ultra-wideband radar microwave breast imaging. To reduce return losses over the antenna bandwidth, a new technique which includes attaching each tapered ridge with a semi-elliptical metallic piece has been suggested. Results show significant improvement of antenna performance. The isolation between the vertical and horizontal polarizations has been investigated by vertically and horizontally oriented field probes at different locations. The proposed horn antenna exhibits almost 40 dB isolation between the two linear polarization signals over the whole frequency bandwidth of the antenna. The gain and ports isolation are also presented. All the results of conducted tests show the efficiency of the designed antenna for dual-polarization radar breast imaging.

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