A low cost and efficient breast cancer detection method with a staircase shaped ultrawide band dielectric resonator antenna using monostatic radar based microwave imaging technique

GAGANDEEP KAUR* and AMANPREET KAUR

Department of Electronics and Communication Engineering, Thapar Institute of Engineering and Technology, Patiala 147004, India
e-mail: gagandhindsa2127@gmail.com; amanpreet.kaur@thapar.edu

MS received 3 February 2022; revised 10 May 2022; accepted 16 May 2022

Abstract. In this article, a staircase-shaped ultra-wide band dielectric resonator antenna (DRA) has been used as a sensor for the detection of breast tumor by monostatic radar-based microwave imaging (MRMWI). The proposed DRA has fractional bandwidth (BW) 98.5% and a high peak gain 5.98 dB along with dual polarization behaviour from 5.12 to 8.2 GHz and 11.02-13.8 GHz. In the MRMWI setup, DRA is placed over the breast phantom at a distance of 7 mm and provides a safe exposure of radiation (<1.6 W/Kg). For simulation, it rotates around the phantom at a fixed interval in elevation (0-180°) and azimuthal (0-360°) planes. It works as a radiate and receives the reflected signals towards and from the scanned area simultaneously. To validate the results, fabricated DRA is connected to a vector network analyzer and rotates (as done for simulation) around the artificial breast phantom. That is a replica of the human breast made from gelatin+sugar, Vaseline and wheat flour+water equivalent to skin, fat and tumor respectively. Afterward S$_{11}$ responses are recorded in the presence and absence of tumor inside the phantom. A significant variation in recorded values leads to the detection of tumors that are processed further in beam-forming algorithms; delay and sum (DAS) and delay-multiply and sum (DMAS) to reform the 2-dimensional image of tumor in MATLAB.

Keywords. Dielectric resonator antenna; phantom of human breast; beam-forming algorithm; 2D imaging; MATLAB.

1. Introduction

Breast cancer is one of the most common diseases among the women. It usually happens when some cancerous or malignant cells start growing hysterialy around the normal body cells [1]. Many clinical techniques such as X-ray mammography, ultra sound and magnetic resonance imaging are available to detect the presence of the breast tumor [2]. But each technique has its own short-comings such as exposure of the ionized radiation along with painful, costly and time consuming treatment, etc. [3]. For early stage breast cancer screening, one of the most promising techniques is microwave imaging (MWI) and it is gaining the attention of numerous researchers. This technique having some advantages such as it is simple, non-ionizing exposure along with un-obstructive, inexpensive and high image resolution of the scanned body area. The basic principle of MWI is based on the large deviation in dielectric properties of malignant and healthy cells [4, 5]. It is mainly classified into two types i.e. monostatic and multi-static MWI. In monostatic MWI, single antenna is placed over the phantom to transmit and receive the signals [6]. Similarly, in multistatic MWI, numerous antennas are placed around the phantom in the form of an array that makes it quite complex and a time consuming method [7]. The procedure followed for MRMWI is simple, speedy and affordable as compared to multistaic MWI. Thus monostatic MWI method is opted for the breast tumor detection.

In MRMWI, the antenna is worked as a sensor and it needs some specific characteristics such as wide bandwidth with multiple resonances, high peak gain, moderately directional radiation pattern and power coupling to the phantom that does not have any effect on the healthy cells [8]. For this aspect, a staircase DRA with an overall volume of 4252.5 mm$^3$ (25 mm×30 mm×5.67 mm) has been proposed for breast tumor detection using MRMWI technique. The proposed DRA shows an ultra-wideband (UWB) characteristics with 5.1-15 GHz of operating frequency range that has been designed (in CST) and fabricated (using photolithography) on an FR4 substrate of 1.57 mm thickness. On top and bottom of the substrate, a layer of copper is deposited as a feedline and a ground plane respectively.
As a final point, a staircase dielectric resonator (DR) of alumina with 4 mm thickness is placed over the feedline. This DR works as a sensor that radiates non-ionizing emissions with safe exposure of radiation (<1.6 W/Kg for 1g of body tissue) [9] on the phantom in two cases: in the presence and absence of tumor (radius = 5 mm) inside the breast phantom. Furthermore, backscattered signals are recorded by the same DRA (mono-statically) in terms of reflection coefficient at different positions by rotating it around the breast phantom from 0 to 180° in elevation and 0-360° in azimuthal planes with fixed interval of 10°. These backscattered signals are used to identify the morphological changes in biological tissues and its position due to the presence of a tumor. For this purpose, the beam-forming algorithms i.e. DAS and DMAS are applied on the resultant backscattered signals to reconstruct a 2D image of the scanned breast area using MATLAB R2018a.

2. Different layers of the proposed DRA’s geometry and design procedure

For the detection of breast tumors using MRMWI system, some important requirements for an antenna are that it should be covered wide-band with multiple resonance frequencies, high peak gain, dual polarization behavior and better resolution power. In order to achieve the above mentioned requirements, a staircase-shaped UWB DRA has been proposed. It is designed and simulated in CST version 2016 with impedance bandwidth of 9.9 GHz (5.1-15 GHz), peak gain of 5.98 dB and elliptical polarization properties. It has four different layers i.e. ground plane followed by substrate (25 mm × 30 mm), feedline and dielectric resonator (DR). The proposed prototype is printed on a FR4 lossy substrate (ε_r=4.4, h=1.57 mm). On the top and base of this substrate, a layer of copper material (35 μm) is deposited to use as a feedline and ground plane respectively as depicted in figures 1(b) and 1(c), respectively. As a final point, a staircase DR of alumina (ε_r=9.8, h=4 mm) is placed over the feed point to use as a patch as shown in figure 1(a). In figures 1(a) to (c), the black section represents the copper, grey represents the FR4 and the dark yellow colour represents the alumina. To enhance the performance of the DRA in terms of bandwidth, return loss, and axial ratio, the geometry of the antenna is optimized by using the defective ground structure (DGS) technique, adding tuning stubs and by modifying DR’s shape as explained with details in section 3. The final optimized dimensions of the proposed antenna are specified in table 1.

2.1 Design procedure and simulation performance of the proposed DRA

The main objective of the present research work is to initially attain a UWB characteristics from the proposed staircase shaped DRA that is modified with rectangular tuning stubs and defected ground structure (DGS). Furthermore, the proposed UWB DRA used as a sensor that identify the presence of the breast tumor of 5 mm. This section gives a complete details about their intermediate steps followed to achieve the desired UWB (5.1-15 GHz) responses as shown in figure 2. And their corresponding responses in terms of S-parameters and axial ratio (AR) are as depicted in figures 3 and 4, respectively.

| Specification | Value (mm) |
|---------------|------------|
| d1=d5         | 10         |
| d2=d8         | 12         |
| d3=d7         | 3          |
| d4=d6         | 14         |
| f1            | 7          |
| f2            | 1          |
| f3            | 12         |
| f4            | 4          |
| g1            | 8.5        |
| g2            | 6          |
| g3            | 12         |
| g4            | 5          |
| g5            | 9          |

Figure 1. Different layers of the proposed DRA. (a) Top view along with DR, (b) Feedline and (c) Ground plane.
• The initial dimension of the rectangular DR i.e. 13 mm × 26 mm has been chosen by considering the dielectric waveguide model (DWM) as given in equation (1) [10].

\[ f_{\text{mnl}} = \frac{c}{2\pi \sqrt{\varepsilon_r}} \sqrt{k_x^2 + k_y^2 + k_z^2} \]  

(1)

Where \( k_x = m\pi/(d_2+d_4) \), \( k_y = n\pi/(d_1+d_3) \) and \( k_z = l\pi/2d \) represents the wave number along x, y and z axis respectively. For the proposed DRA the values of \( d_1=10 \text{ mm}, \ d_2=12 \text{ mm}, \ d_3=3 \text{ mm}, \ d_4=14 \text{ mm}, \ d=4 \text{ mm}, \ m/n/l=1 \) and gets the resonant frequency of 7.2 GHz that is relatively close to the simulated resonant frequency of 8.05 GHz.

• The conventional DRA geometry (DRA1) along with rectangular DR, simple microstrip feed and full ground plane (25×30 mm²) excites the tri-band operations i.e. 7.65-8.22 GHz, 9.35-9.92 GHz and 13.2-15.2 GHz (BW=27.1%) as shown in figure 3 (dotted blue color plot). The DRA1 geometry provides the entirely linear polarization (AR above 10 dB) except for 6.8 and 11.4 GHz of frequency.

• To improve the fractional bandwidth, return loss and AR of the conventional antenna, two rectangular stubs each of dimension 7 mm×1 mm are joined on both sides of feedline (geometry DRA2). By these slots the total volume 1.352 cm³ of DR reduces to 1.068 cm³ (21% reduction of the total volume) and also reduction in Q-factor. This leads to the improvement in operational bandwidth and allows it to excite two additional frequency bands from 10.71 to 11.3 GHz, 11.77-12.1 GHz along with 7.65-8.22 GHz, 9.3-10.14 GHz, and 13.2-16.2 GHz (BW=44.6%) frequency bands as shown in figure 3 (dotted red color plot). By DRA2 geometry the antenna provides the AR <10 dB for two sub-bands i.e. 7.86-8.2 GHz and 9.6-10.02 GHz.

• After that, the shape of the rectangular DR is modified into staircase shaped by etching two rectangular slots each of dimensions 12 mm×3 mm from its corners as shown in figure 2 (geometry DRA3). Through these alternations the antenna provides multiple bands of 7.9-8.92 GHz, 10.71-12.1 GHz, 12.7-14.7 GHz, 14.7-16.2 GHz with wider bandwidth (BW= 49%) as shown in figure 3 (dotted green color plot). DRA3 geometry also offers the excellent improvement in the AR from 7-8.8 GHz and 11.2-14 GHz.
Figure 5. E-field distribution plot in XZ and YZ planes for different operating modes (a) TE_{111}, (b) TE_{211} and (c) TE_{221}.

Figure 6. Fabricated prototype (a) Staircase DR, (b) Feedline and (c) Ground structure.
Finally to get an UWB and dual polarization behaviour, the geometry of the ground plane is modified by using DGS technique. That disturbs the total current distribution and helps in decreasing the size of the DRA. The proposed DRA geometry allows the antenna to excite desired UWB characteristics from 5.1 to 15 GHz (BW=98.5%) as depicted in figure 3 (solid pink color plot). The AR of the DRA is also improved significantly from 5.12 to 8.2 GHz and 11.02-13.8 GHz.

3. DRA operations

3.1 Validation of field modes of the proposed DRA

While radiation the proposed staircase shaped DRA proficiently exhibits a fundamental mode i.e. TE$_{111}$ and three higher order modes i.e. TE$_{211}$ and TE$_{221}$ in XZ and YZ planes. The different modes are calculated by equation (1) at the resonant frequencies i.e. 7.2, 8.2 and 10.6 while the simulated resonant frequencies are 8.05, 9.1 and 11.2 for different modes such as TE$_{111}$, TE$_{211}$ and TE$_{221}$ respectively. Figure 5(a) shows an E-field distribution of the dominant mode TE$_{111}^x$ and TE$_{111}^y$ as 19378 V/m and 22977 V/m at the frequencies of 8.05 and 8.52 GHz respectively. Figure 5(b) shows E-field distribution of 22262 V/m (TE$_{211}^x$) and 23554 V/m (TE$_{211}^y$) at frequencies of 9.1 GHz and 9.37 GHz respectively. Figure 5(c) shows E-field of 26339 V/m (TE$_{221}^x$) and 21414 V/m (TE$_{221}^y$) at the frequencies of 11.2 and 11.8 GHz respectively leads to the generation of dual polarization behaviour (AR<10 dB) by the proposed DRA for the frequency band 5.12-8.2 GHz and 11.02-13.8 GHz.

4. Fabrication and testing of the proposed DRA

For practical testing of breast tumor detection, primarily DRA is fabricated using a wet etching photolithography process. The proposed prototype consists of a layer of FR4 lossy substrate. On the top and bottom of this substrate, a feedline and a ground structure (DGS) of copper material are deposited as shown in figures 6(b) and 6(c), respectively. At last a staircase shaped DR of material alumina (cut using the water jet cutting technique) is staked over the feedline with the help of panacol vitralit as shown in figure 6(a). For the validation and testing of the results, a SMA female connector is soldered at the termination point of the feedline for activation purpose. After that, SMA connector is allied to the vector network analyzer’s (VNA) probe through coaxial cable of 50 Ohms impedance. Figure 7(a) shows the variation among simulated (solid blue plot) and measured (dotted pink plot) S$_{11}$ parameter. It indicates that the proposed DRA effectively shows UWB characteristics from 5.1 to 15 GHz for simulated and 5.38-12.3 GHz, 12.52-13.2 GHz and 13.54-14.2 GHz for measured case and gets approximately 84% matching between them. Figure 7(b) shows the Snapshot of the measured S-parameter on VNA screen. Subsections 4.1 and 4.2 explained brief summary of the broadband gain and polar plot of the proposed antenna.
4.1 Broadband gain

The combined broadband gain plots for simulated and measured values are depicted in figure 8. The proposed DRA achieved the simulated gain 5.98 dB and measured gain 6.05 dB at 7.3 GHz and 7.52 GHz frequency respectively. The DRA shows an average gain of 4.5 dB (simulated) and 4.58 dB (measured). Thus the proposed DRA is an appropriate choice for the biomedical applications i.e. breast tumor detection.
4.2 Polar radiation pattern

The 2D polar plot radiation patterns are experimentally measured by placing the proposed DRA (in XZ and YZ plane) inside an anechoic chamber. For this measurement setup, a horn antenna (transmitter) is placed at a distance of 100 cm from the proposed DRA (receiver), and the results are in the form of polar plots are observed on VNA. The polar plot of simulated and experimentally measured results at two resonant frequencies of 9.37 and
10.3 GHz which are depicted in Figures 9(a) and (b), respectively. Additionally, the LHEP (left hand elliptical polarization) and RHEP (Right hand elliptical polarization) 2D polar plot of the proposed staircase shaped DRA is depicted in figures 9(c) and (d) at resonant frequencies of 7.3 GHz and 11.8 GHz, respectively is an appropriate selection for the detection of breast tumor.

5. Microwave Imaging Procedure for the detection of breast cancer

The hemispherical mimic of breast phantom is designed with similar electrical properties as that of human breast and simulated in CST version 2016 to detect the tumor inside it. The total volume of the breast phantom is around
16,747 mm$^3$ with a total radius of $r_3=20$ mm and has three layers of skin ($2$ mm) followed by fat ($r_2=18$ mm) and tumor ($r_1=4$ mm) as shown in figure 10(a). In MRMWI the proposed DRA is placed over the breast phantom at distance $D$ and it rotates in both azimuthal and elevation plane as shown in figures 10(b) and (c), respectively. When $D$ is $7$ mm, it provides the safe exposure of the radiation with specific absorption rate (SAR) is $1.53$ W/Kg for 1g of tissue at simulated resonant frequency of $9.37$ GHz but with $D<7$ mm the SAR is varies from $1.73$ to $15.8$ W/Kg.

For practical testing, the breast phantom model is made artificially from crystalline gelatin + sugar like skin ($\varepsilon_r=45-65$, $\sigma = 5-20$ Sm$^{-1}$), petroleum jelly-like fat ($\varepsilon_r=2.36$, $\sigma = 0.0012$ Sm$^{-1}$) and wheat-flour + water like tumor ($\varepsilon_r=23$, $\sigma = 2.57$ Sm$^{-1}$) [11] as shown in figure 11(a). For the validation of results (S-parameter), the fabricated DRA is coupled to the VNA and rotates around the artificial breast phantom in the same approach as that done for simulation in CST (azimuthal plane from 0 to $360^\circ$ and in elevation plane from 0 to $180^\circ$) as depicted in figure 11(b). Figures 12(a) and (b) show the simulated and measured S-parameter comparison plot for the two cases: with (dotted orange curve) and without (solid sky blue curve) placement of tumor. The noticeable deviation in S-parameter at resonant frequencies of $6.2$, $8.5$, $10.2$, $12.13$ and $13$ GHz for simulated and $6$, $7.56$, $9.7$, $11.8$ and $13$ GHz for measured has been observed. Thus from this, it is concluded that the reflection coefficient with the presence of a tumor (black color) is shifted upward due to high water content in tumor. The recorded backscattered signals ($S_{11}$) mainly consist of strong reflections from tumor and also from skin and fat. For the identification of tumor, there is a need to eliminate the unwanted reflections i.e. from skin and fat. Thus for this purpose we opted subtraction method to calibrate the signals as given in equation (2) [12]. In this method, a tumor of $5$ mm is inserted in the phantom at $(0,0)$ coordinates and reflections are recorded at each position as Reflection coefficient with tumor. Then reflections are recorded without placing any tumor in breast phantom as Reflection coefficient without tumor

\[
\text{Reflection – coefficient (x, y)} = \text{Reflection – coefficient}^{\text{with – tumor}}(x, y) - \text{Reflection – coefficient}^{\text{with – tumor}}(x, y)
\]  

These results are utilized in different beam-forming algorithms to get a clear 2D image of the breast tumor cell. The next subsections illustrate the use of this data in two main image reconstruction algorithms. But the subtraction
method is not practically feasible to identify the location of the tumor. Several interference removal algorithms have been developed to find out the size and position tumor.

5.1 Measured results with an artificial breast phantom

5.2a Delay and sum (DAS): After calibration the data is processed for DAS algorithm to remove the clutters, the calibration is used to remove the environment signals and keep only the mark of tumors. The mathematical formula for the DAS algorithm is given in equation (3) [13]. In this algorithm, firstly the received S-parameter is recorded at individual antenna positions by rotating it around the breast phantom. Then time-delays for all received Reflection-coefficient (x, y) are calculated based on position of the transmitter and receiver antenna, these time delayed signals are summed up as $S(t)$. Next step is to get the synthetic focus point for tumorous signals. The S-parameters where there is a good difference between the values of with and without tumor which actually represents the reflections
from any malignant cells are added coherently (because the signals from the tumor has the same frequency and phase so their addition give rise to high peak signals as focus point at a particular frequency) and the reflections from normal cells are added incoherently (because of different phase and frequency they may cancel out after addition) for the calculation of intensity level. The energy or intensity of the S(t) parameter values from the tumor affected area gets amplified compared to the normal skin reflections at frequencies of 5.98, 7.6, 9.58, 11.75 and 13 GHz because adding coherent signals will raise the intensity level. But a very minor difference in the intensity level of skin and tumor’s reflection coefficients particularly at frequency 5.98, 11.75 and 13 GHz and maximum at 7.6 GHz as illustrated in figure 13(a). The process is repeated for all the focal points within the breast phantom and final image of breast tumor is plotted using MATLAB in x-y plane as shown in figure 13(b). It was observed that radius of the detected tumor is around 4 mm at coordinate (-1,-1.5).

\[ S(t) = \sum_{i=1}^{M} x_i(t - \text{delay}_i) \]  

(3)

5.2b Delay multiply and sum (DMAS): DMAS has more contrast, low side lobes and better resolution than DAS. The DMAS method uses summation of pair-wise multiplications of signals to estimate scattered energy profile as mentioned in equation (4) [13]. For each focal point, time alignment synthetically focuses received signals at that point. The resultant signals are used to reconstruct the 2D image of breast tumor with enhanced quality at particular frequency 7.6 GHz as depicted in figure 14(a) using equation (4). It is observed that energy level at this frequency is much improved from 450 to 1500 dB. But at the other frequency values the energy level is reduced i.e. less than 300 dB and gets only one amplified tumorous signal. That helps in the reconstruction of 2D and offers the approximate position (0,-1) and radius of the breast tumor 4.23 mm. The 2D microwave image is reconstructed to get a clue about the position of the breast phantom as shown in figure 14(a).

\[ Y(t) = \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} x_i(t - \text{delay}_i) \ast x_j(t - \Delta \text{delay}_j) \]  

(4)

Where M is a number of antenna rotation, i and j represent the different position of the antenna.

The efficiency of the proposed DRA for microwave imaging applications is verified by comparing its performance with some exiting DRA designs in terms of size, operating frequency, imaging techniques and experimental validations are as given in table 2. In the reported work, the researchers purposed a complex and large sized DRA [14–18, 20] for microwave imaging techniques with only narrow or wider frequency bands. Additionally, they did not validate their results experimentally with artificial breast phantom [14–20]. The proposed DRA is simple in structure, small in size and provides UWB characteristics. It detects the presence of breast tumors by reconstructing a 2D image in MATLAB. As well its simulated results are also verified by placing the fabricated DRA over an artificial breast phantom. Hence the proposed research work is one step ahead of the existing research work in the area of imaging and can be effectively used for suggested biomedical applications.

6. Conclusion

This research article presents a MRMWI for the detection of breast tumor using an UWB DRA sensor. For this purpose staircase DRA has been designed and simulated in CST 2016. It has an operating frequency range of 5.1-15 GHz, high peak gain of 5.98 dB (simulated) and dual polarization behavior (AR<10 dB) for 5.12-8.2 GHz and 11.02-13.8 GHz frequency bands. In MRMWI procedure, DRA is rotating around the breast phantom at different focal positions with fixed interval of 10\(^\circ\) (0-180\(^\circ\) in elevation and 0-360\(^\circ\) in azimuthal plane). And transmit the signals towards it that has three different layers as skin, fat and tumor with different electrical properties. After that backscattered signals are recorded (for both cases: without and with placement of breast tumor inside phantom) by rotating the same DRA. For practical testing, the similar procedure is followed by the fabricated DRA and artificial breast phantom. And different backscattered signals are recorded on VNA. These recorded data is processed further for DAS and DMAS data independent imaging algorithms and 2D images are reconstructed in MATLAB from which we clearly observe the position of breast tumor. It is also observed that the DAS algorithm detects the breast malignancies but with the poor image quality. To overcome the drawbacks of DAS, the DMAS algorithm was introduced that not only improves the image quality but also provides accurate localization of the tumor.

Declarations

Conflict of interest The authors of the manuscript have no conflict of interests.

References

[1] Morrow M, Waters J and Morris E 2011 MRI for breast cancer screening, diagnosis, and treatment. The Lancet. 378: 1804–1811

[2] Patel B K, Garza S A, Eversman S, Lopez-Alvarez Y, Kosiorek H and Pockaj B A 2017 Assessing tumor extent on contrast-enhanced spectral mammography versus full-field digital mammography and ultrasound. Clinical Imaging. 46: 78–84
[3] Bohra S and Shaikh T 2016 UWB Microstrip Patch Antenna for Breast Cancer Detection. *International Journal of Advanced Research in Electronics and Communication Engineering*. 5: 88–91

[4] Karli R, Ammor H and El Aoufi J 2014 Miniaturized UWB microstrip antenna for microwave imaging. *WSEAS Transactions on Information Science and Applications*. 11: 214–220

[5] Lazaro A, Villarino R and Girbau D 2011 Design of tapered slot Vivaldi antenna for UWB breast cancer detection. *Microwave Opt. Techno Lett.* 53: 639–643

[6] Kaur G and Kaur A 2020 Breast tissue tumor detection using “S” parameter analysis with an UWB stacked aperture coupled microstrip patch antenna having a “+” shaped defected ground structure. *International Journal of Microwave and Wireless Technologies*. 2: 635–651

[7] Klemm M, Craddock I J, Leendertz J A, Preece A and Benjamin R 2009 Radar-based breast cancer detection using a hemispherical antenna array-Experimental results. *IEEE Transactions on Antennas and Propagation*. 57: 1692–1704

[8] Mahmud M, Islam M T, Misran N, Almutairi A F and Cho M 2018 Ultra-wideband (UWB) antenna sensor based microwave breast imaging: A review. *Sensors*. 18: 2951

[9] Shahira Banu M A, Vanaja S and Poonguzhali S 2013 UWB microwave breast cancer detection using SAR. *International Journal of Advanced Electrical and Electronics Engineering*. 2: 87–92

[10] Adnan S, Abd-Alhameed R A, See C H, Hraga H I, Elfergani I T and Zhou D 2010 A compact UWB antenna design for breast cancer detection. *PIERS online*. 6: 129–132

[11] Al-Zuhairi D T, Gahl J M, Al-Azzawi A and Islam N E 2017 Simulation, design and testing of a dielectric embedded tapered slot UWB antenna for breast cancer detection. *Progress in Electromagnetics Research C*. 79: 1–15

[12] Mozaffarzadeh M, Hariri A, Moore C and Jokerst J V 2018 The double-stage delay-multiply-and-sum image reconstruction method improves imaging quality in a LED-based photo-acoustic array scanner. *Photo Acoustics*. 12: 22–29

[13] Mobashsher A T 2016 *Wideband Microwave Imaging System for Brain Injury Diagnosis*. A thesis submitted for the degree of Doctor of Philosophy at The University of Queensland Australia

[14] Abas S 2013 Dual-polarized, broadside, thin dielectric resonator antenna for microwave imaging. *IEEE Antennas and Wireless Propagation Letters*. 2: 380–383

[15] Huang W and Kishk A A 2009 Compact dielectric resonator antenna for microwave breast cancer detection. *IET Microwaves, Antennas & Propagation*. 3: 638–644

[16] Suwanta P, Krachodnok P and Wongson R 2017 Wideband inverted L-shaped dielectric resonator antenna for medical applications. In: *Proceeding of IEEE International Conference on Computational Electromagnetics (ICCEM) Kuma- moto*, Japan, pp. 188-189

[17] Gupta A, Reddy S and Gangwar R K 2018 Dielectric resonator antenna array for X-band and microwave imaging applications. *Microw Opt. Technol. Lett*. 60: 960–965

[18] Rana B and Kumar S 2017 Microstrip line fed wideband circularly-polarized dielectric resonator antenna array for microwave image sensing microwave/millimeter wave. *Sensors*. 1: 1–4

[19] Singh U, Kanaujia B K and Singh A 2019 Novel circularly polarized dielectric resonator antenna for microwave image sensing application. *Microwave Opt. Techno Lett*. 61: 1821–1827

[20] Nawaz H and Kiyani A 2016 Ku-band dielectric resonator antenna array for microwave imaging. *Microwave Opt. Techno Lett*. 58: 1651–1655