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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Design of Dumbbell Shaped DGS-Notch Patch Antenna for Microwave Imaging System

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DOI: https://doi.org/10.30880/ijie.2020.12.06.012
Received 08 April 2020; Accepted 11 June 2020; Available online 02 July 2020

Abstract: In this paper, square Microstrip Patch Antenna with notch is designed with dumbbell shaped DGS for microwave imaging system. The antenna is designed on dielectric substrate, FR-4 with relative permittivity, ε_r = 4.7 and thickness, 1.6mm. The dumbbell shaped DGS act as the resonant structures and is placed as the ground layer of the antenna. Different location and size of dumbbell shaped DGS are simulated and analyzed. The result of return loss, radiation pattern and antenna gain are simulated using Electromagnetic Simulation Tools, fabricated and measured using Wave and Antenna Training System (WATS 2002). The design shows better performance with return loss of -38.99 dB and higher antenna gain of 6.20 dB compare to the conventional design, with return loss of -30.21 dB and antenna gain of 5.48 dB respectively.

Keywords: dumbbell, DGS, imaging, return loss, radiation, gain

1. Introduction

Microwave imaging technique is one of the medical imaging techniques that used non-ionizing electromagnetic (EM) signals to analyze the hidden tumor in the cancer area at the frequency range of hundreds of megahertz to hundreds of gigahertz [1]. The microwave imaging equipment involved the microwave source, the antennas and the radio frequency switch. The antennas play the important roles in the microwave imaging as it has the ability to transmit and receive the signal. Several studies have been outlined to improve the microwave component performance. Initially, the Photonic Band Gap (PBG) was introduced by John and Yablonovitch [2]. PBG technique used the rejection band of certain frequency that provided by the periodic structure on the ground plane. However, there are difficulties faced in the PBG structure modelling for microwave and millimetre-wave components due to the radiation from periodic etched defects, lattice spacing, lattice shape, lattice number and the fraction of relative volume [3]. Besides that, there is another technique known as Ground Plane Aperture (GPA) which has been studied for 3-dB edge coupler and bandpass filters. At the ground plane, the GPA technique can easily embrace the microstrip line embedded with a centered slot [4]. Nevertheless, the GPA width forms a critical effect on the microstrip line characteristic impedance which limits the level of return loss [5].

In order to solve the problems faced by PBG and GPA techniques, Defected Ground Structure (DGS) was proposed by Park et al. [6]. DGS is described as the closed-packed geometrical slots implanted on the microwave circuits' ground plane. A single defect or a number of periodic and aperiodic defects structures maybe comprised in DGS [7-8]. Therefore, the periodic and aperiodic defects engraved on the ground plane of planar microwave circuits are

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also referred as DGS. The DGS can be consider as a simplified form of Electronic Band Gap (EBG) which exhibits a band-stop property.

For this research, the dumbbell shaped Defected Ground Structure (DGS) is chosen to improve the performance of the proposed microstrip patch antenna with notch [9]. The analysis of the DGS performance is made by comparing the different locations of dumbbell shaped DGS proposed under the microstrip line and the different sizes of the dumbbell shaped DGS proposed placed under the patch. The antenna will be designed on FR-4 substrate with permittivity of 4.7 by using the Electromagnetic Simulation Tools. The final design is then fabricated and measured by using Wave and Antenna Training System (WATS 2002).

The design specification is the most important when designing the antenna. There are several parameters need to be concerned and calculated to ensure that the antenna meets the requirements. The proposed design of the antenna in this research is the square microstrip patch antenna with notch.

1.1 Square Microstrip Patch Antenna

The proposed square microstrip patch antenna is designed by using the substrate FR-4 with relative permittivity, 4.7 and the substrate thickness of 1.6 mm [10-11]. The operating frequency is 2.4GHz [12]. FR-4 is used as the substrate due to low cost and high dielectric constant which results in a smaller patch size and high tangent loss that causes the lower gain [13]. The microstrip line analysis is used to design the antenna which normally has 50Ω impedance that can meet with the 50Ω microstrip line. For that reason, the microstrip line used is perfectly matched with the antenna. Therefore, the width of the feedline, W_f is presented as;

$$Z_0 = \frac{Z_f}{\sqrt{\varepsilon_{eff}(1.393 + \frac{W}{h} + \frac{2}{3}\ln(\frac{W_f}{h} + 1.444))}} \tag{1}$$

With

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + 12\frac{h}{W_f})^{-\frac{1}{2}} \tag{2}$$

Where $Z_f = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 376.8\Omega$, Z_0 is the 50Ω impedance, h is the substrate thickness, W is the width of the patch, ε_{eff} is the effective dielectric constant and ε_r is the dielectric constant of the substrate.

The actual length of the patch, L is computed by the formula;

$$L = L_{eff} - 2\Delta L \tag{3}$$

With

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \tag{4}$$

And

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(\frac{w}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{w}{h} + 0.8)} \tag{5}$$

Where ΔL is the extension length, L_{eff} is the effective length, c is the speed of light, 3×10^8 m/s, f_0 is the operating frequency of the antenna, ε_{eff} is the effective dielectric constant, h is the substrate thickness and w is the width of patch.

The width of the ground plane, W_g and the length, L_g of the ground plane can be determined by the formula;

$$W_g = 6h + W \tag{6}$$

$$L_g = 6h + W \tag{7}$$

Where h is the substrate thickness and W is the width of the patch. The feedline length, F_i based on [14] can be expressed as;

$$F_i = 10^{-4}(0.001699\varepsilon_r^7 + 0.13761\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 4043\varepsilon_r + 6697)\frac{L}{2} \quad (8)$$

Where ε_r is the dielectric constant of the substrate which must in the range of 2 to 10 and L is the length of the patch. Besides that, there is also the gap between the patch and the inset fed, G_{pf} which the gap usually is 1 mm [15]. The parameters of microstrip patch antenna that have been calculated are summarized in Table 1.

Table 1- Parameters of the proposed antenna

Parameters	Unit (mm)
Width of the patch, W	37.02
Length of the patch, L	37.02
Length of the feedline, F_i	12
Width of the feedline, W_f	2.932
Length of the ground plane, L_g	46.62
Width of the ground plane, W_g	46.62
Gap between the patch and the inset fed, G_{pf}	1

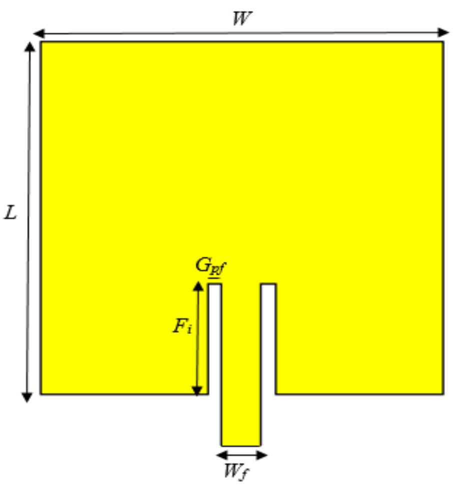


Fig.1 - Geometry View of Conventional Microstrip Patch Antenna

1.2 Square Microstrip Patch Antenna with Notch and Defected Ground Structure

According to [16-17], the notch width, W_n which is located symmetrically at the top center of the patch can be determined by using the equation;

$$W_n = \frac{W}{n} \quad (9)$$

Where W is the width of the patch and n is the number which n is in the range of 2 to 10. Meanwhile, the length of notch, L_n fix at the ratio of $L/10$ which L is the patch length.

The dimension of proposed dumbbell-shaped DGS as shown in Fig. 2 can be obtained based on the equation [18]:

$$a = 96.44^{\frac{2}{0.923}} . f_0^{-\frac{2}{0.923}} . \varepsilon_r^{-\frac{0.9414}{0.923}} . w^{-\frac{0.8896}{0.923}} . g^{\frac{0.0013}{0.923}} . h^{-\frac{0.4593}{0.923}} \quad (10)$$

Where $b=a$, g is an initial value that need to be selected, w is calculated based on the ratio $\frac{w}{g}$, h is the thickness of the substrate in mil, ε_r is the dielectric constant of the substrate and f_0 is the operating frequency in GHz.

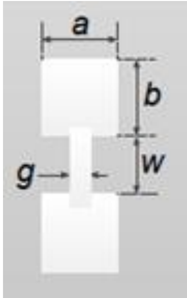


Fig. 2 - The Dimension of Dumbbell Shaped DGS

2. Results and Discussion

The result of the proposed antenna is shown in Fig.3 with gain of -30.21 dB.

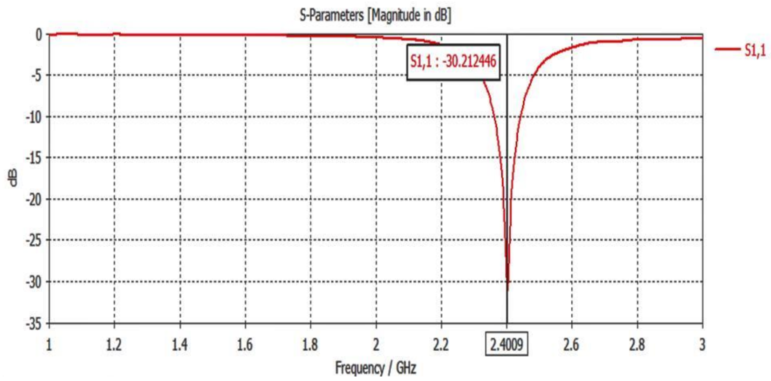


Fig. 3 - Proposed antenna result

The notch is then designed at the top center of the patch. The value of '*W*/10, *W*/9', '*W*/8', '*W*/7', '*W*/6', '*W*/5', '*W*/4' , '*W*/3'and '*W*/2' where W is the width of the patch with the fixed value of notch width, *L*n which is 2.945 mm varied accordingly and summarized in Table 2.

Fig. 4 shows the result from different notch width, W_n with different return loss and the antenna. Among all the notch width that are simulated, W_n = *W*/9 is the best notch width with the minimum return loss -28.21 dB, bandwidth 76.29 MHz and maximum antenna gain 5.47 dB. The return loss first decreases with decreasing notch width and after achieving its maximum negative, the return loss start to increase again when the notch width varied [16]. The maximum negative of the return loss could match the impedance perfectly. Besides that, the highest antenna gain would be able to transmit and receive the amount of signal effectively in the same direction. Therefore, the notch size of 3.272 mm × 2.945 mm with width and length respectively is selected as the design for placing dumbbell shaped DGS under the microstrip line and patch respectively.

Table 2 - Performance Analysis of W_n from *W/2* to *W/10*

Notch Width, W_n	-10 dB Bandwidth (MHz)	Return Loss (dB)	Antenna Gain (dB)
W/2	80.87	-20.34	5.42
W/3	83.16	-22.75	5.44
W/4	78.60	-24.51	5.45
W/5	71.70	-24.84	5.46
W/6	80.85	-25.65	5.46
W/7	76.28	-26.15	5.47
W/8	78.56	-27.92	5.47
W/9	76.29	-28.21	5.47
W/10	80.87	-26.38	5.46

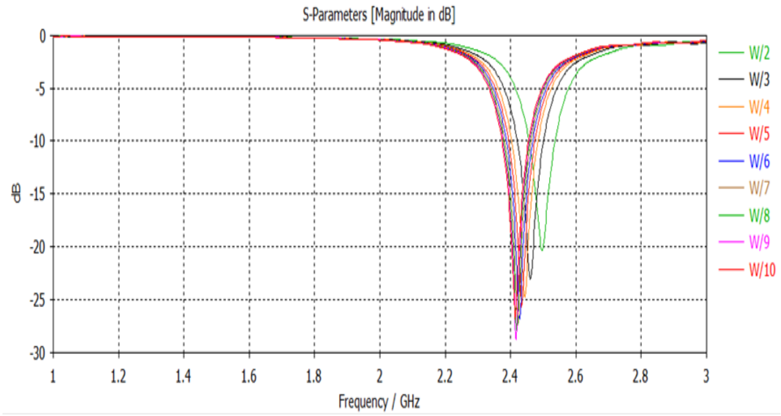


Fig.4 - The Comparison of W_n from $W/2$ to $W/10$

The dumbbell shaped DGS placed under the microstrip line acts as the interrupter to perturb the current path [19]. In [24] a dumbbell is also design for UWB applications. To determine the dimension of dumbbell shaped DGS, Eqn. 10 is used by initially assuming dimension, w = 19.5 mm and dimension, g = 2.5 mm which will give a-arm and b-arm, 4.6 mm respectively. The location of dumbbell shaped DGS as shown in Fig. 5 is placed based on the distance of dumbbell shape DGS from the end of microstrip line, x.

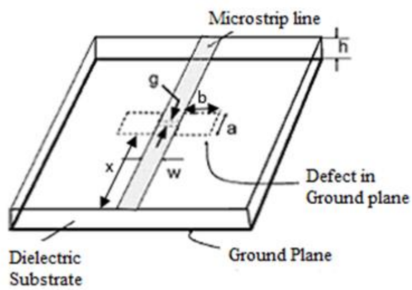


Fig. 5 - Perspective View of the Dimension of Dumbbell Shaped DGS under the Microstrip Line

By assuming the dumbbell shaped DGS dimension w = 14 mm and dimension g = 2 mm, the a-arm and the b-arm will be equal to 6.33 mm respectively. The microstrip patch antenna patch size and the dimension of dumbbell shaped DGS need to be adjusted by placing the dumbbell shaped DGS under the microstrip line at the best location in order to obtain the S-parameter return loss lower than -10dB. Therefore, the dumbbell shaped DGS is placed under the middle of microstrip line between the bottom of the patch and the bottom of the microstrip line which the distance of dumbbell shaped DGS from the end of microstrip line, x = 4.1975 mm. Fig. 6 shows the result after dumbbell shaped DGS is placed underneath the transmission line.

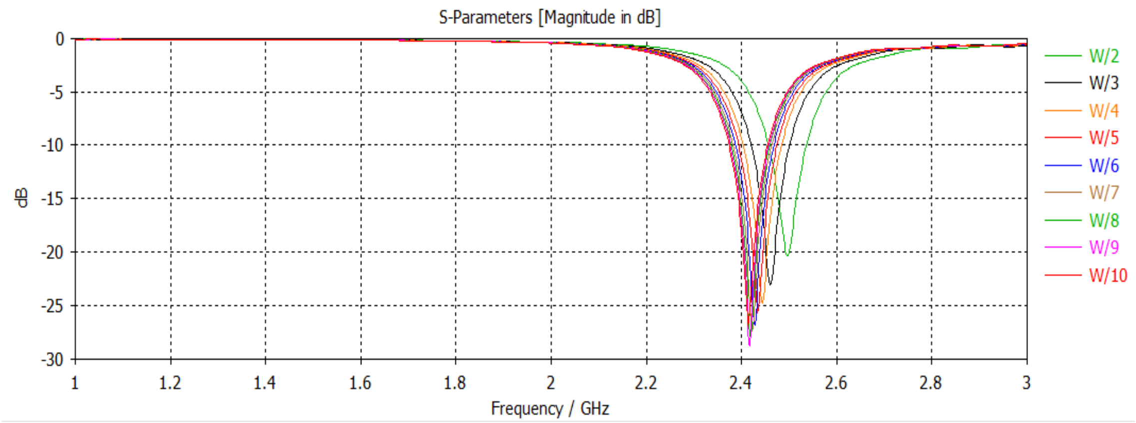


Fig. 6 (a) - The Result Obtained when Dumbbell Shaped DGS under Microstrip Line

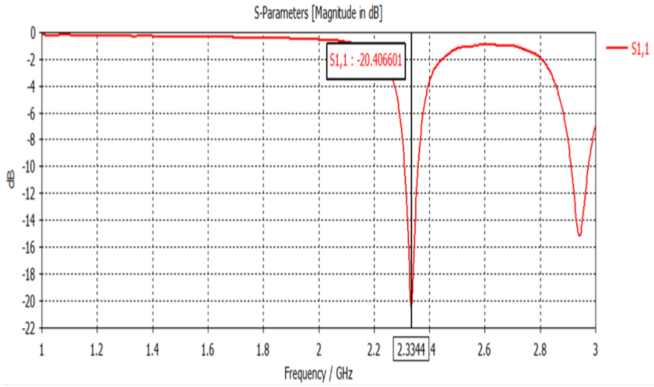


Fig. 6 (b) - The Result Obtained when Dumbbell Shaped DGS under Microstrip Line

The most effective parameter of the antenna is the patch size with parameters of 26 mm and the dimension of dumbbell shaped DGS, the *a*-arm and the *b*-arm reduced to 5 mm with maintaining dimension w = 14 mm and dimension g = 2 mm. The best location as the initial simulation to place the dumbbell shaped DGS under the microstrip line is the distance of dumbbell shaped DGS from the end of microstrip line, x = 2.275 mm. This is shown in Fig. 7.

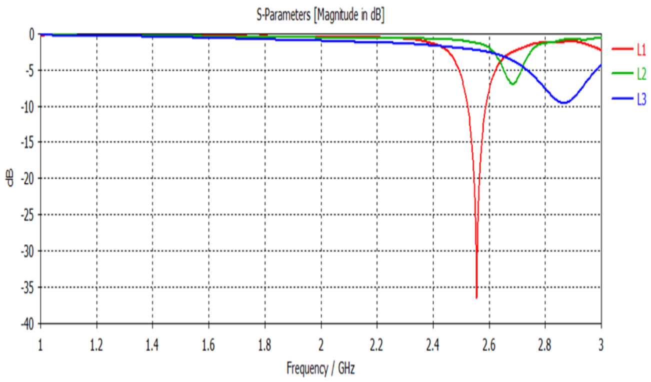
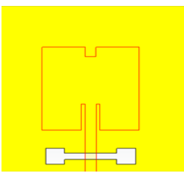
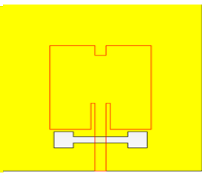
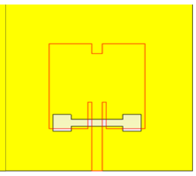


Fig.7 - Comparison of the Location of Dumbbell Shaped DGS Located under Microstrip Line

Different location of dumbbell shaped DGS placed under the microstrip line and its result for both return loss and antenna gain is shown in Table 3. Among all the location, *L1*, which the dumbbell shaped DGS located 2.275 mm from the end of microstrip line is the best location with the minimum return loss -34.05dB, bandwidth 64.84 MHz and antenna gain 6.12dB, followed by *L2* which the dumbbell shaped DGS located 7.275 mm from the end of microstrip line with return loss -6.97dB and antenna gain 4.96dB. Lastly, the third location (*L3*) which the dumbbell shaped DGS located 12.275 mm from the end of microstrip line give the return loss of -9.62dB and antenna gain 4.66dB respectively.

Table 3 - Performance Analysis of L1 to L3

Details	*L1*	*L2*	*L3*
Location of dumbbell shaped DGS			
Distance of dumbbell shape DGS from the end of microstrip line, x (mm)	2.275	7.275	12.275
-10 dB Bandwidth (MHz)	64.84	None	None
Return Loss (dB)	-34.05	-6.97	-9.62
Antenna Gain (dB)	6.12	4.96	4.66

The location of dumbbell shaped DGS placed under the microstrip line between the bottom of the patch and the end of the microstrip line shows the better return loss performance and antenna gain as compare to the dumbbell shaped DGS placed near to the patch or the end of the microstrip line [20]. Besides that, the reduction of patch size also able to affect the performance of return loss when the dumbbell shaped DGS utilize under the microstrip line [21]. As the patch size reduce, the return loss shows the better result as compare to the original patch size calculated.

The size of the dumbbell shaped DGS located under the patch also able to affect the return loss and the antenna gain [22]. Therefore, the dimension of dumbbell shaped DGS located with dimension w = 14mm, g = 2mm and a-arm = b-arm = 5mm. Different design is then simulated based on changing the sizes of the dumbbell shaped DGS and is shown in Fig. 8.

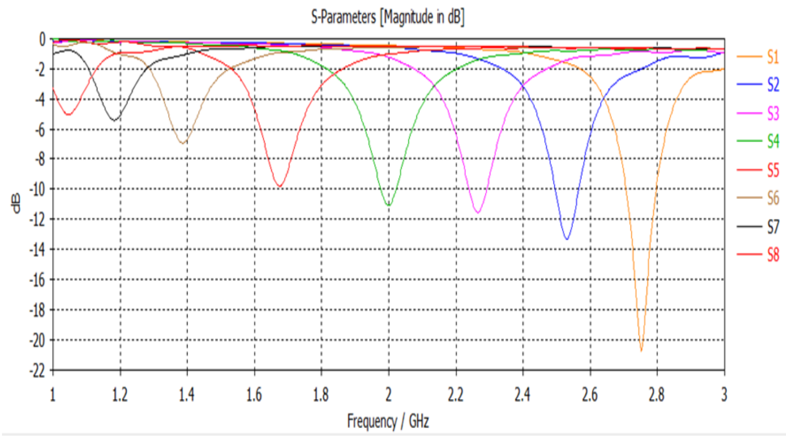


Fig. 8 - Comparison of the Size of Dumbbell Shaped DGS Located under Patch

Fig. 9 shows the different dimension of dumbbell shape DGS with different return loss and antenna gain. From the overall size that had been simulated, the dumbbell shaped DGS with dimension w = 6mm, dimension g = 0.125 mm and a arm = b arm = 1mm is the best size of dumbbell shape DGS with the best return loss which is -20.75 dB, bandwidth 90.01 MHz and antenna gain 6.02 dB. The result shows the larger the size of dumbbell shaped DGS would cause lower current density distribution and the smaller the size of dumbbell shaped DGS would increase the current density distribution. This is due to smaller size of the dumbbell shaped DGS has the higher rate to discontinue the current on the ground plane.

Simulation	S1	S2	S3	S4	S5	S6	S7	S8
a = b (mm)	1	2	3	4	5	6	7	8
w (mm)	6	8	10	12	14	16	18	20
g (mm)	0.125	0.25	0.5	1	2	3	4	5
-10 dB Bandwidth (MHz)	90.01	64.84	53.33	51.11	None	None	None	None
Return Loss (dB)	-20.75	-13.29	-11.52	-11.17	-9.81	-6.92	-5.41	-5.03
Antenna Gain (dB)	6.02	5.88	5.50	4.92	4.27	3.65	3.60	3.46

Fig. 9 - Analysis of Different Size of Dumbbell DGS as Ground Layer

In order to get the best design of square microstrip patch antenna with notch and dumbbell shaped DGS, the dumbbell shaped DGS with the dimension w = 14mm, g = 2mm and a arm = b arm = 5mm located 2.275mm from the end of microstrip line combine with the dumbbell shaped DGS with the dimension of w = 6mm, g = 0.125mm and a-arm = b-arm = 1mm located under the patch between the bottom of notch and feedline. Fig. 10 shows the geometry view of the combinational design.

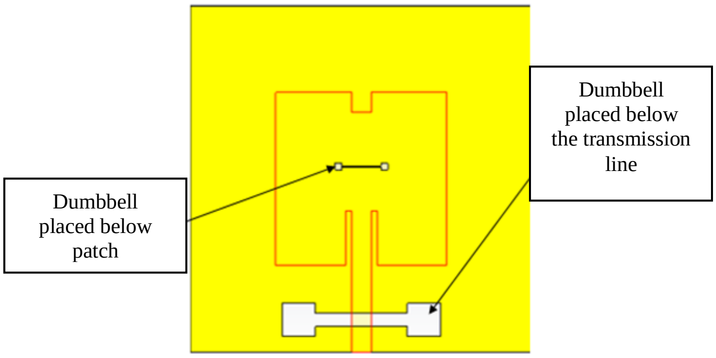


Fig. 10 - Geometry View of the Combinational Design

According to Table 4, the result obtained shows the performance of the combinational design of notched square microstrip patch antenna with DGS and the conventional square microstrip patch antenna. The combinational design has higher return loss which is -36.74 dB and bandwidth is about 64.23 MHz as compare to the result from the conventional design which is -30.21 dB and bandwidth is about 79.73 GHz.

Table 4 - Analysis between Combinational and Conventional Design

Parameters	Combinational Design	Conventional Design
Frequency (GHz)	2.52	2.4
-10 dB Bandwidth (MHz)	64.23	79.73
Return Loss (dB)	-38.99	-30.21
Gain (dB)	6.20	5.48

In Fig. 11, the frequency of the combinational design is obtained at 2.52 GHz compare to conventional design.

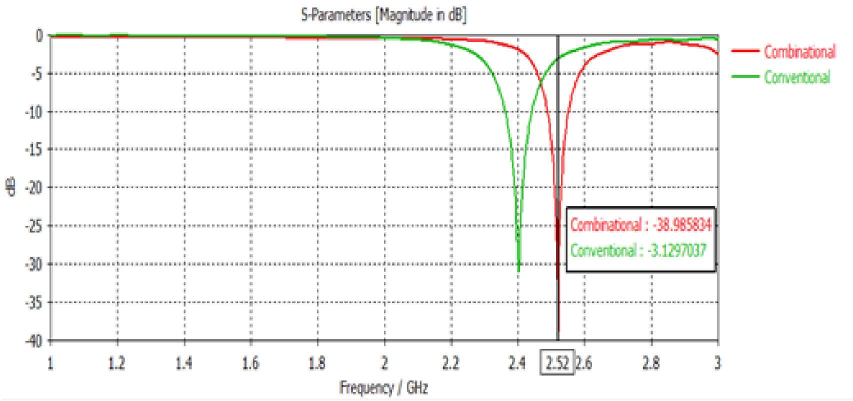


Fig. 11 - Comparison S11 Parameter Result of Combinational Design and Conventional Design

Fig. 12 shows the comparison of the radiation pattern between the combinational design of notched square microstrip patch antenna with DGS and conventional square microstrip patch antenna. The main lobe of the combinational design indicates antenna gain is 6.20 dB better than that of conventional design which the antenna gain is 5.48 dB. This shows that the antenna gain of the combinational design is highly desired and good enough to radiate the signal in the microwave imaging system [23].

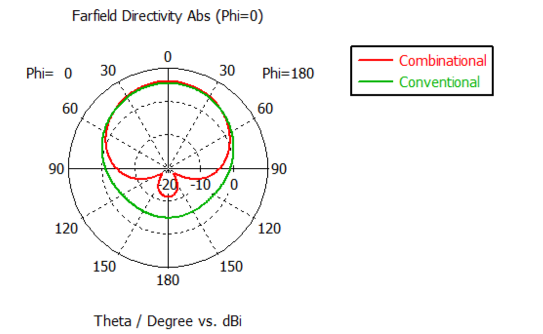
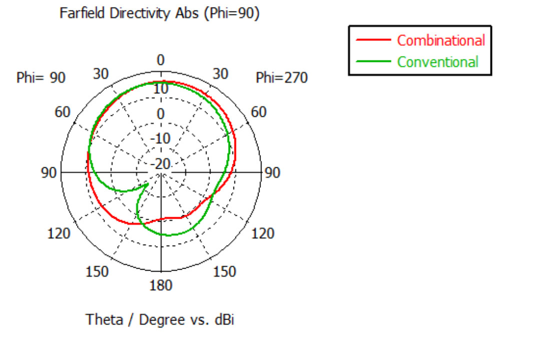
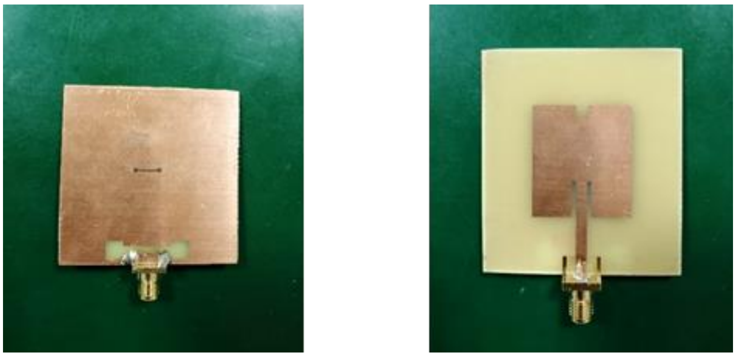
E-Plane	
H-Plane	

Fig. 12 - Comparison of the Radiation Pattern between Combinational and Conventional Design

The proposed antenna is fabricated and characterized with the Wave and Antenna Training System (WATS 2002). The antenna is printed on FR-4 substrate material with a relative dielectric constant, ε_r of 4.7 and thickness, *h* of 1.6mm. Fig.13 shows the fabricated notched square microstrip patch antenna with DGS.



(a) (b)

Fig. 13 - (a) Top View and (b) Bottom View of the Fabricated Notched Square Microstrip Patch Antenna with DGS

The radiation pattern of antenna is measured in far field region. Measured and simulated results is shown in Fig. 14. It is shown that the simulated and measured radiation pattern of the antenna at 2.4 GHz for simulation and 2.45 GHz for measurement are demonstrated when phi = 0^o for E-plane and phi = 90^o for H-plane. However, the radiation pattern obtained from measurement result is difference from the simulation result. This is because of the limitation of the experiment set up such as the environment issues, equipment calibration, and the antenna type used for the receiver that affect the measurement results.

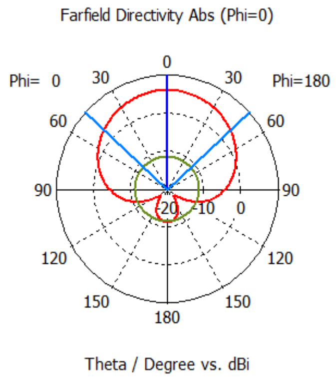
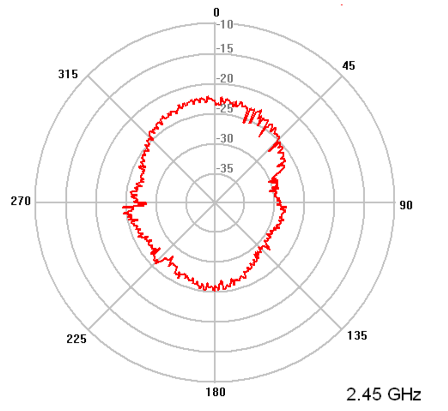
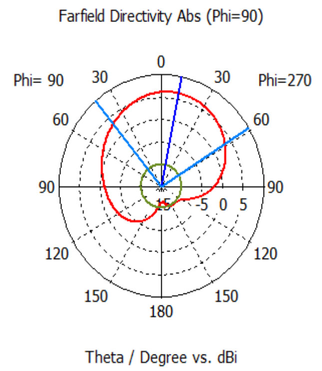
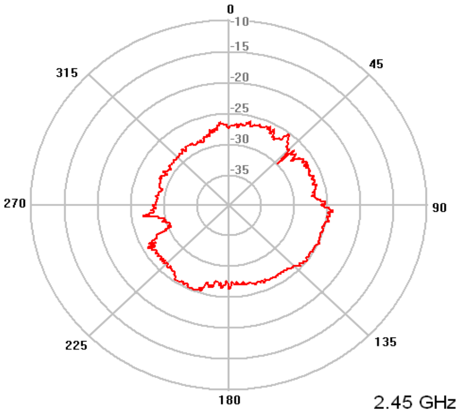
Radiation Pattern	Simulation (2.4 GHz)	Measurement (2.45 GHz)
E-Plane		
H-Plane		

Fig. 14 - Simulation and Measurement Results of the Proposed Antenna

3. Conclusion

This research introduced the dumbbell-DGS placed at the ground layer of the proposed antenna that can improved its performance with gain of 6.20 dB with good return loss of 38.99dB at the bandwidth of 64.23 MHz. The measurements also been carried out in the microwave and antenna laboratory. But due to interference and calibration of equipment, environmental factor, the results are difficult to achieve. Nevertheless, the proposed antenna with dumbbell DGS can be used as one of the important elements in microwave imaging system.

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