Size Reduction of Circular Microstrip Patch Antenna through Metamaterial

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Abstract— **This paper recommends a circular microstrip patch antenna with DGS structure to be used in Wi-Fi application. The combination of a circular microstrip patch antenna with Defected Ground Structure (DGS) structures at the ground plane is proposed to reduce the size of antenna. The antenna has been designed to improve the performance. The patch antenna is designed to resonate at 2.45 GHz. Metamaterial characteristics with negative permittivity and permeability of the proposed DGS structures have been verified using Nicolson-Ross-Weir (NRW) method. A complete simulation has been done using the Computer Simulation Technology Microwave Studio (CST-MWS) version 2011. The design was fabricated on Rogers RO3003 with permittivity, ε_r=3.00 and thickness, h=0.75mm. The measurements have been carried out to verify the performance of antenna by a Vector Network Analyzer (VNA). The results show that the size of antenna was reduced by 67% compared to conventional antenna. The best return loss obtained from the design was -45.77976 dB. The bandwidths for metamaterial and conventional antenna are 20 MHz.**

Index Terms— **metamaterial, circular patch antenna, DGS structure and return loss.**

I. INTRODUCTION

RECENTLY, microstrip patch antennas become the most demanding antenna based on their applications, which has some merits like low weight and fabrication cost, and operating in high frequency range [1]. Nowadays there are many other government and commercial applications, such as mobile radio and wireless communications that use microstrip antennas [2, 3]. Microstrip antennas however have main drawback in terms of narrow bandwidth, low efficiency and relatively large size [4, 5]. The important topic in microstrip antenna is to obtain a broad bandwidth and to miniaturize the patch size [6]. The narrow bandwidth can be enhanced by increasing the substrate thickness; however, this will lead to a greater surface wave which will decrease the antenna efficiency and degrade the antenna pattern [7]. To overcome the drawbacks, microstrip patch antennas are incorporated with different materials to improve the potential parameters of the antenna. Among them, metamaterials are found to be most suitable [8].

Metamaterial characteristics are theoretically investigated in this paper. Metamaterials are artificially constructed materials having electromagnetic properties not generally found in nature (negative refractive index) [9]. Metamaterials are also known as Left-Handed Metamaterial (LHM) and Backward Wave Material (BWM) where the permeability and permittivity were simultaneously negative [10]. Negative permittivity means that the materials are physically unique, have unusual realizable response functions and may not be easily found in nature [11]. Victor Veselago, a Russian Physicist was the first person responsible for discovering the concept of metamaterials in 1967 [12]. The Veselago's intuition remained silent for 29 years until in 1996 when J.B Pendry proposed his design of Thin-Wire (TW) structure that exhibits the negative value of ε and the Split Ring Resonator (SRR) with a negative value of μ. Based on this discovery, Smith [13] combined the two structures which represented the first experiment Left-Handed Metamaterial (LH MTM) prototype.

In recent years, there have been several new concepts applied to distributed microwave circuits. One such technique is *defected ground structure* or DGS, where the ground plane metal of a microstrip (or stripline, or coplanar waveguide) circuit is intentionally modified to enhance performance. DGS has been an increasing interest in microstrip technology and one of the unique techniques to reduce the antenna size. DGS is realized by an etched lattice shape in the ground plane of planar circuits and microstrip antennas. DGS have advantages in the area of microwave filter design, planar resonators, high characteristic transmission lines, couplers, dividers/combiners, oscillator, microwave amplifies and microstrip antenna[14]. It is also used in the cross polarization reduction, mutual coupling reduction and suppression of the higher order harmonics in the microstrip antenna technology [15]. The defect in the ground plane of planar transmission lines such as microstrip will disturb the shield current distribution and also change the characteristic of the transmission line such as capacitance and the inductance. The presence of DGS realizes the metamaterial substrate.

Referring to [16], the design, simulation and fabrication of a Left-Handed Metamaterial (LHM) structure are presented. The project used the combination of themodified square rectangular Split Ring Resonator (SRR) and the Capacitance Loaded Strip (CLS) to obtain the negative value of permeability, μ and the negative permittivity, ε. NicolsonRoss-Wierapproach was used to identify the double negative region. However, this project was unable to reduce the side and back lobe. The gain of the microstrip antenna with LHM structure could be further improved if the side and back lobe can be reduced.

Other than that, previous technical paper [17] presents the circular patch antenna on metamaterial substrate for C-band applications at 4.7 GHz. The researcher has shown an improvement in terms of return loss, size and gain directivity. This researcher used a split ring for the defected ground structure. A Flame Retardant 4 (FR-4) was applied as the main substrate. The result shows that, the circular patch antenna on metamaterial substrate better than conventional circular patch antenna on FR-4 only in term of return loss -24.2 dB, directivity gain 5.66 dB and gains 1.99 dB.

II. METHODOLOGY

The design approach of this project is represented in the flow chart in Fig. 1. Basically, the processes are involving the design of DGS and two antennas; metamaterial and conventional patch antenna. For a complete analysis, both of the antennas were fabricated in a same substrate but with different properties; metamaterial and nature materials. The antennas have been measured after been fabricated. The data obtained from the measurement was analyzed. The data then compared to simulation results.

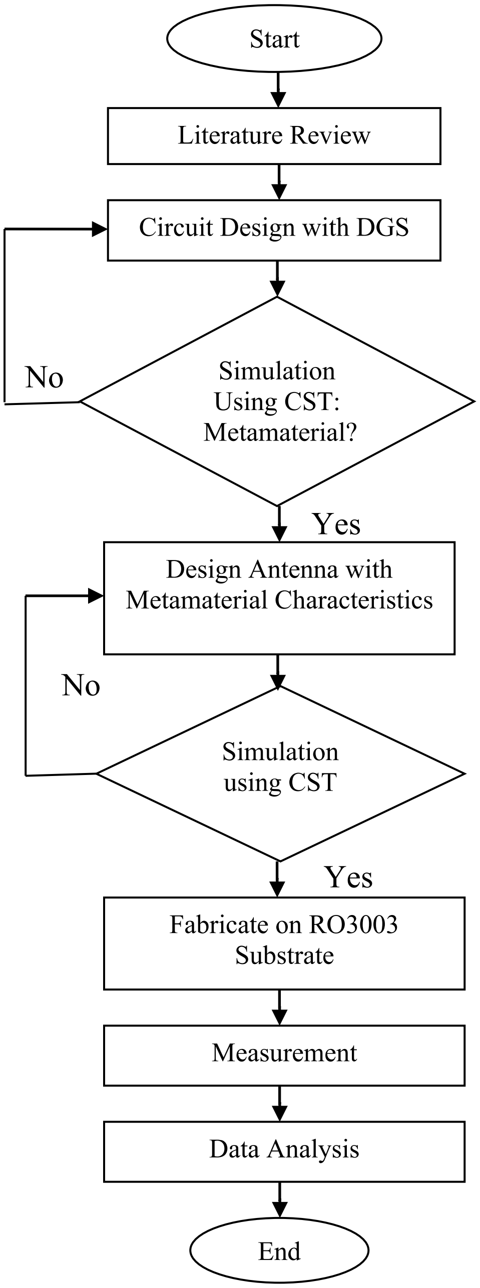


Fig. 1. Flow chart of the project design.

A. *Project Research*

This project was started from a metamaterial antenna and DGS structure. Theory of the subject matter has been carefully studied and understood. Many researchers have claim that an antenna with DGS structure and metamaterial properties produce a better performance compare to conventional antenna. From the research, DGS structure would produce metamaterial characteristics within certain frequencies.

B. *DGS Structures Design*

Second step of this project is a design rectangular split ring of DGS structure and a patch antenna. The DGS geometry was designed by a modification of a rectangular split ring, so that the substrate behaves as metamaterial at 2.45GHz. Metamaterial antenna was designed using Computer Simulation Technology (CST) Microwave Studio version 2011.

C. *Metamaterial Test*

There are several methods to verify the permittivity and permeability of a substrate that can be analyzed from S-parameters. Nicolson-Ross-Weir (NRW) was chosen since it is the most popular and accurate technique to attain the permittivity and permeability. This technique is widely used to convert the S-parameters and provides an easy way to plot of the permittivity value of the metamaterial versus frequency.

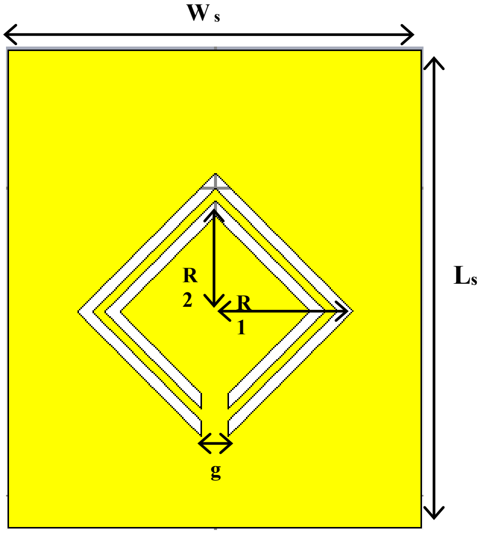


Fig. 2. Structure of the Rectangular Split Ring DGS

TABLE I
DIMENSION OF DGS STRUCTURE AND SUBSTRATE

Parameters	Values (mm)
R1	9.00
R2	7.20
g	1.80
W_s	27.00
L_s	31.00

The geometries of the rectangular split ring structure was shown in Figure 2. The DGS stuctural was placed on the ground side. The main substrate of this project is RO3003. This type of substrate has been chosen due to several factors such as low dielectric loss and suitable for high frequency which is up to 40 GHz. The dimensions of DGS structure and substrate are tabulated in Table I whereas the characteristics of this substrate was shown in Table II.

TABLE II
ROGERS RO3003 SUBSTRATES CHARACTERISTICS

Characteristics	Values
Permittivity, ε_r	3.00
Permeability, μ_r	1.00
Thickness, h	0.75 mm
Copper cladding	0.035 mm

The rectangular split ring was constructed and the simulation was run to obtain the metamaterial characteristic. The differences between antenna on metamaterial and on natural RO3003 substrate was the size of the overall layout. It shows that, the size of metamaterial antenna was smaller than the size of the conventional antenna on natural RO3003 substrate.

D. *Patch Antenna Design*

In order to design a circular patch antenna operating at resonant frequency 2.45GHz, a suitable dielectric substrate with relative permittivity ε_r = 3.00 and of thickness h = 0.075mm was chosen. *The main parameters* are shown below:

i) Radius of the circular patch antenna

$$a = F\left\{1 + \frac{2h}{\pi F \varepsilon_r}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{-1/2} \qquad (1)$$

where

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \qquad (2)$$

ii) Length of the transmission line

$$L_f = \frac{\lambda_g}{4} \qquad (3)$$

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \qquad (4)$$

$$\lambda_o = \frac{c}{f_r} \qquad (5)$$

iii) Inset feed

$$y = \frac{10^{-4}L}{2}\left(\begin{array}{l} 0.001699\,\varepsilon_r^{7} + 0.13761\,\varepsilon_r^{6} - \\ 6.1783\,\varepsilon_r^{5} + 93.187\,\varepsilon_r^{4} - \\ 682.69\,\varepsilon_r^{3} + 2561.9\,\varepsilon_r^{2} - \\ 4043\,\varepsilon_r^{1} + 6697 \end{array}\right) \qquad (6)$$

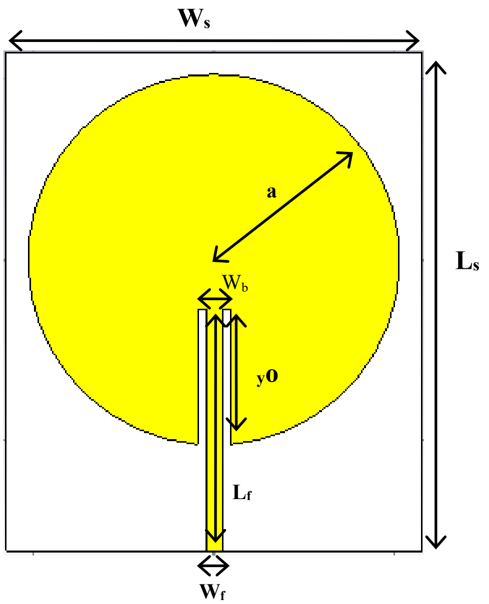


Fig. 3. Patch antenna without DGS.

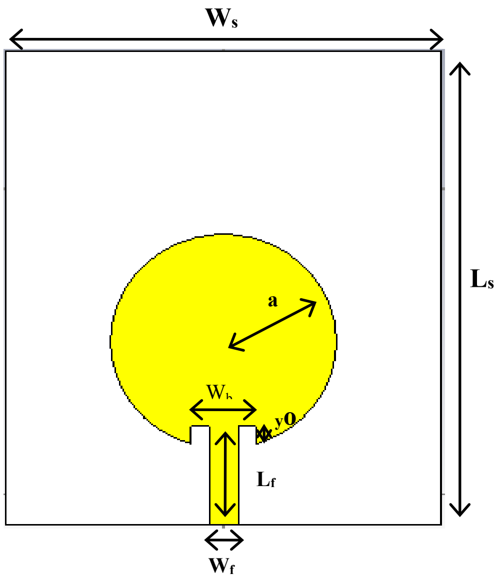


Fig. 4. Patch antenna with DGS.

TABLE III
DIMENSIONS OF CIRCULAR MICROSTRIP PATCH ANTENNA WITH AND WITHOUT DGS

Parameter	Conventional Antenna (mm)	Metamaterial Antenna (mm)
Ws	45.916	27.000
Ls	55.206	31.000
a	20.708	7.000
L_f	26.748	6.450
W_f	1.800	1.800
W_b	3.600	4.000
yo	14.981	1.158

Besides getting the desired output, an optimization process was performed in CST microwave studio to obtain the best antenna response. In order to maintain the impedance of the transmission line, the width of the transmission line has to be constant along the optimization process. The other parameters such as radius, width, length and the length of transmission line were continuously varied until achieve the required results. All optimization values were shown in table III.

III. RESULT & DISCUSSION

In this research, the antenna performances were investigated through simulation and measurement process. The simulation results were obtained from the CST-MW whereas the measurement results were obtained from Vector Network Analyzer (VNA) measurement. The overall results have been recorded and shown in session *A* and *B*.

A. Simulation Results

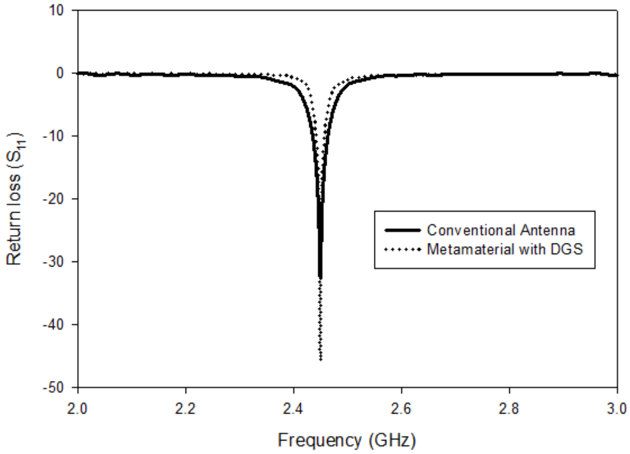
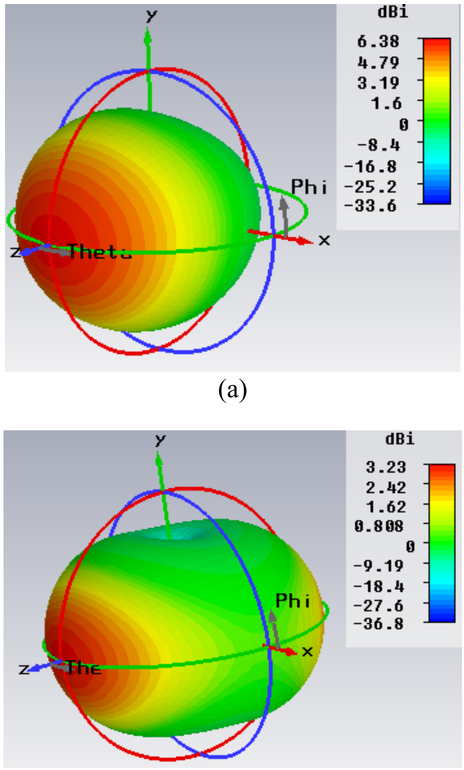


Fig. 5. Comparison of return losses between conventional antenna and metamaterial antenna

Figure 5 shows the simulation results for return loss (S_{11}) of conventional and metamaterial antennas. It shows the best value of return loss from both antennas after optimization. It was shown that the S_{11} for the circular patch antenna with DGS structure has a better performance of -45.77976 dB compared to the patch antenna without DGS which has only -32.531564 dB. These values prove that the metamaterial (DGS) able to improve the return loss of antenna. The smallest value of return loss is required in order to minimize the reflection wave and simultaneously able to maximize the transmitting power. It means that the antenna can operate with a better performance. The conventional and metamaterial antenna produces the same narrow bandwidths which are about 20 MHz size of bandwidth, such is suitable for Wi-Fi application.



(a)

(b)

Fig. 6. 3D plot of antenna directivity in dBi; a) conventional antenna b) metamaterial antenna

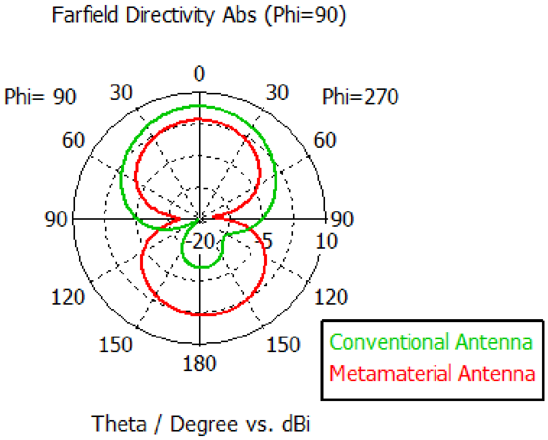
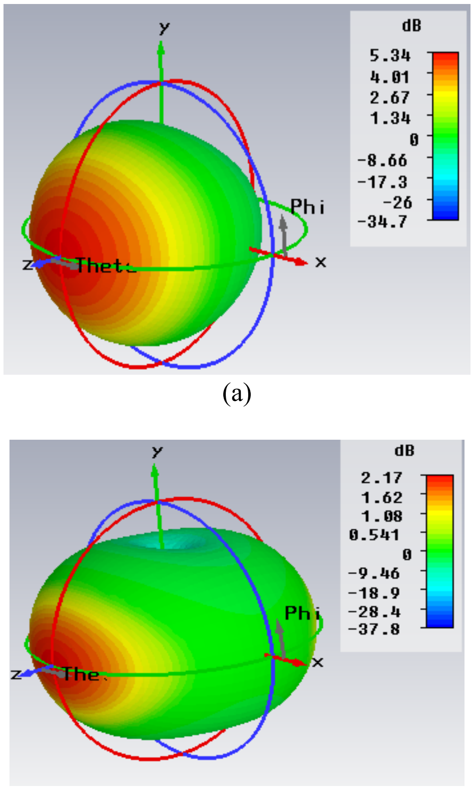


Fig. 7. Polar plot of antenna directivity in dBi

Figure 6 a) and b) represents 3D plot of antenna directivity for conventional and metamaterial antennas. Figure 7 represents polar plot of antenna directivity for conventional and metamaterial antenna respectively. From figure 6 a) and b), there are found that the metamaterial antenna produced lower directivity compared to the conventional antenna which is about 49.37%. Since the conventional antenna produced greater directivity value, the metamaterial antenna can operate signal from both sides which are from front and back. From figure 7, the beamwidth (-3dB) of polar plot for conventional and metamaterial antenna are 89.5° and 86.6° respectively. The metamaterial antenna produced the bi-directional polar plot that compatible for Wi-Fi application. Bi-directional pattern operate from both front and back of the antenna.



(a)

(b)

Fig. 8. 3D plot of antenna gain in dB; a) conventional antenna b) metamaterial antenna

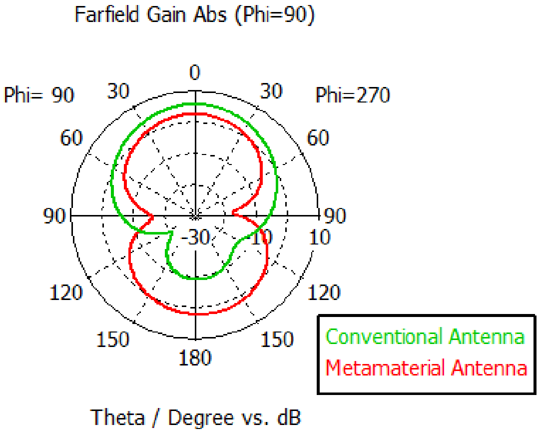


Fig. 9. Polar plot of antenna gain in dB

Figure 8 a) and b) represents 3D plot of antenna gain for conventional and metamaterial antennas. Figure 9 represents polar plot of antenna gain for conventional and metamaterial antenna respectively. Same as antenna directivity, metamaterial antenna produced lower gain compared to the conventional antenna based on figure 8 a) and b). It is because of the metamaterial antenna in figure 9 produces a bi-directional antenna, then the gain is divide by two for each signal. Since the conventional antenna produced greater gain value, the metamaterial antenna can operate signal from both sides. From figure 9, the bi-directional antenna is suitable for the proposed application.

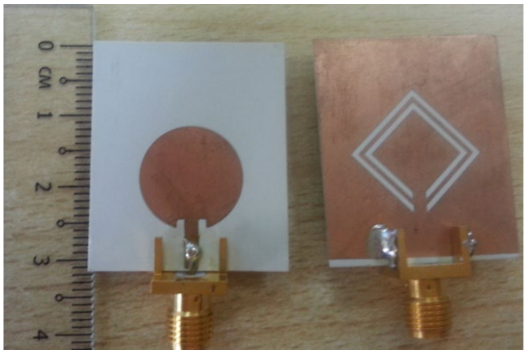
TABLE IV
COMPARISON BETWEEN SIMULATION PERFORMANCE OF METAMATERIAL ANTENNA AND CONVENTIONAL ANTENNA

Description	Conventional Antenna	Metamaterial Antenna	Difference (%)
Radius, a (mm)	20.708	7.000	66.20
Width, W_s (mm)	45.916	27.000	41.20
Length, L_s (mm)	55.206	31.000	43.85
Return Loss, S_{11} (dB)	-32.531564	-45.77976	40.72
VSWR	1.048399	1.0103343	3.63
BW (MHz)	20	20	0
Patch Area (mm)	45.916 x 55.206	27.000 x 31.000	67.00

Table IV shows the overall comparison between metamaterial antenna and conventional antenna. The VSWR for metamaterial antenna is 1.01:1 and it means 1.01 times greater than the minimum standing wave value. An ideal transmission line would have a VSWR of 1:1. It means that, all the power transfer and no reflected power. From the table above, both of antennas shows the good estimate of VSWR. The decreasing of the radius, width and length are clearly stated and it is been proved that the size of the antenna is reducing by 67% compared to conventional antenna.

B. Measurement Results

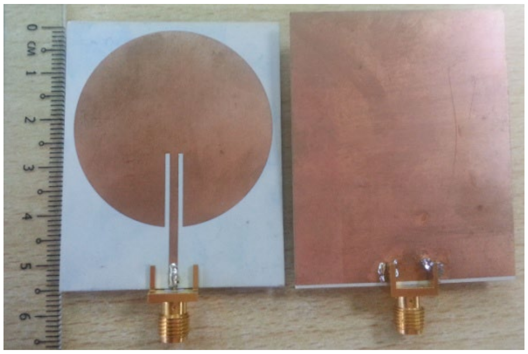
Figure 10 represents the metamaterial antenna (patch antenna with DGS) that has been fabricated. Figure 10 a) shows the view of circular microstrip patch antenna placed at the front of the substrate while figure 10 b) shows the rectangular split ring shaped DGS structure at the ground plane.



(a) (b)

Fig. 10. Patch antenna with DGS. a) front view b) back view

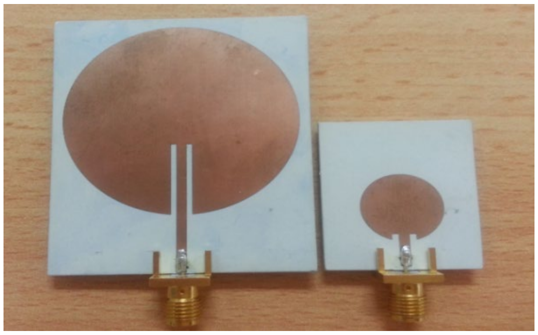
Figure 11 depicts the view of circular microstrip patch antenna without DGS structures. Figure 11 a) and b) shows the front view of the antenna and the back view (ground plane) respectively.



(a) (b)

Fig. 11. Patch antenna without DGS. a) front view b) back view

Based on the figures above, it can be seen that size of circular microstrip patch metamaterial antenna is different with the conventional antenna. Metamaterial antenna in figure 12 is much smaller than conventional antenna in figure 13. From the measurement result, it is also shown that the DGS structures reduced the antenna size.



(a) (b)

Fig. 12. Comparison circular microstrip patch antenna with and without DGS a) without DGS b) with DGS

Figure 12 shows the comparison circular microstrip patch antenna with and without DGS. From the figure, it is prove that, the size of the antenna with DGS is much smaller than circular microstrip patch antenna without DGS. The total of reducing size of the antenna is 67%. Due to this matter, the cost of fabrication will eventually reduce.

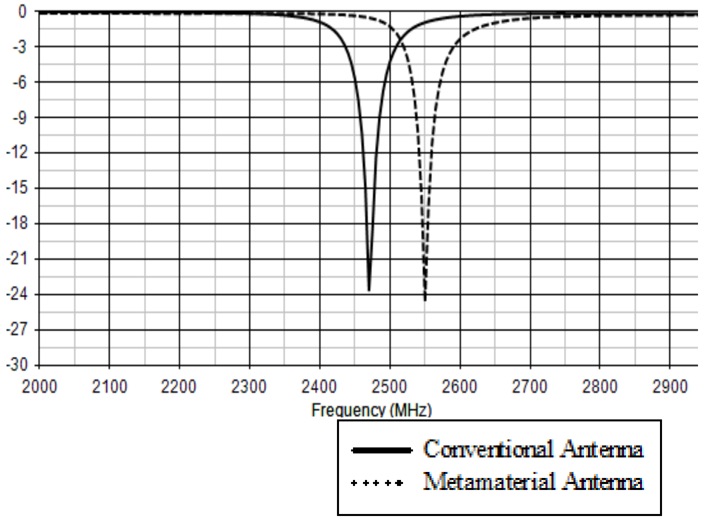


Fig. 13. Comparison of return losses between conventional antenna and metamaterial antenna

Figure 13 represents the measurement result of Return Loss (S_{11}) for metamaterial and conventional antenna. It is shown that the resonant frequency of the antennas is slightly shifted. The metamaterial antenna resonate at 2.55 GHz which is shifted to the right by 100 MHz while the conventional antenna resonate at 2.47 GHz which is shifted to the left by 20 MHz. Normally, the differences between these two readings are due to disturbance or interference that affect the circuit in an open air environment. It is also occurs due to corrosion of copper during fabrication process. However, both antennas produce good return loss (S_{11}) less than -10 dB which is agree with figure 5. The metamaterial antenna exhibits better return loss than conventional antenna as about -24.615 dB and -23.715 dB respectively. The return loss values for simulated and measured result are significantly differing due to losses in equipment such as connector. From the graph, the bandwidths are same for both conventional and metamaterial antenna with simulation and measurement result which is 20 MHz.

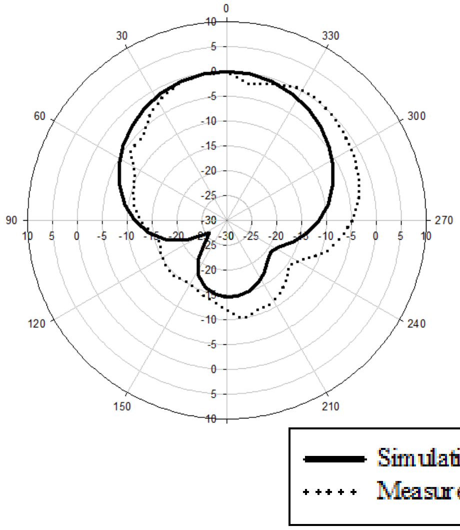


Fig. 14. Comparison of radiation pattern for conventional antenna between simulation and measurement result

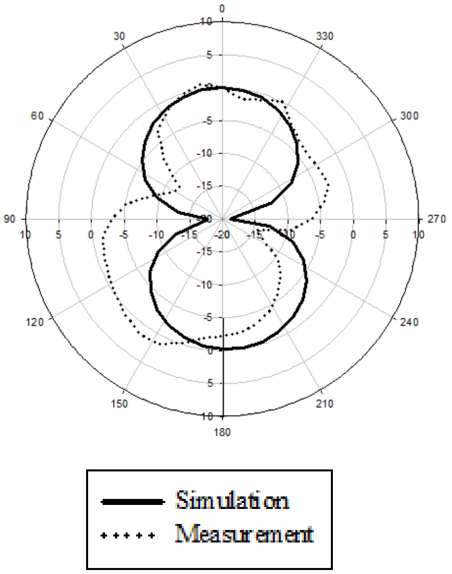


Fig. 15. Comparison of radiation pattern for metamaterial antenna between simulation and measurement result

Figure 14 and 15 show the radiation pattern for conventional antenna and metamaterial antenna between simulation and measurement result. From both figures, the radiation patterns are almost similar between simulation and measurement. The results are significantly different due to disturbance or interference that affects the antenna in an open air environment during measurement.

IV. CONCLUSION

In this paper, the circular microstrip patch antenna with DGS structure has been simulated, fabricated and measured. The objective of this project has been achieved to reduce the size of antenna through metamaterial. The size of metamaterial antenna is much smaller than conventional antenna about 67%. The conventional and metamaterial antenna characteristics have been investigated. Both simulated and measured results show the performance of the DGS structure toward microstrip antenna.

V. FUTURE DEVELOPMENT

Some improvements can be done to increase the antenna directivity and gain in future research. Array configuration is one of the methods to increase the gain of the antenna. The DGS structure can be design using different shape and dimensions. In the other hand, the metamaterial antenna can be design using different substrate and structure. Different type of patches and feeding techniques might affect the performance of the antennas while different types of antenna will affect the antenna's performance.

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