Circular Shape Metamaterial Antenna with Defect Ground Structure (DGS)

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***Abstract*— This paper presents a Circular Shape Metamaterial Antenna with Defect Ground Structure (DGS) at operating frequency of 5.4GHz. The construction of circular-shape DGS at ground plane contributes the metamaterial features to the antenna. Conventional antenna with and without DGS structure has been simulated, fabricated and measured. The simulation design has been done using Computer Simulation Technology (CST) microwave studio and both antenna were fabricated on RO3003 substrate with dielectric constant 3 and 0.75mm height. The proposed antenna was enhancing the performance the antenna in term of return loss and directivity. The minimum specification of return loss from simulated result is -10dB cutoff.**

***Keyword*—Metamaterial Antenna, Conventional Antenna, Defect Ground Structure (DGS), Directivity, Return loss.**

I. INTRODUCTION

The theory of metamaterial or negative index refraction was introduced by V.G.Veselago in 1968. It studied that, the effects of a left-handed material with the simultaneously negative permittivity ε_r and permeability μ_r along with a negative refractive index. By using this theory, phase velocity propagates in opposite direction to group velocity or it can define as "backward wave" propagation [1]. In 2001, the first structure was proved by Shelby Smith and Schultz at the University of California, San Diego which is split ring structure [2]. Then in 2005 another three new structures were investigated started by symmetrical ring structure, then an omega structure, and finally an S structure [3]. In the previous research work [4], proposes a Small Patch Antenna on Metamaterial Substrate. The metamaterial was constructed by using symmetrical-ring structure and the antenna and it design for X-band application at frequency 11.28GHz. The antenna was constructed from a combination of the Flame Retardant 4 (FR-4) and copper metal in a symmetrical-ring. The metamaterial antenna has reduced the circuit size of antenna by maintain the amplitude of the return loss and enhancing the bandwidth of patch antenna. This antenna is very suitable for the application that is needed to cover a wide area because it provides the larger bandwidth compared to conventional antenna.

The antenna used in this project is a microstrip patch antenna print on a substrate. Microstrip antennas have unique features and attractive properties such as low profile, light weight, compactness and conformability in structure. With those advantages, the antennas can be easily fabricated and integrated in solid-state devices [5]. However conventional antenna has low gain and directivity. It also has a small wavelength and most signals will reflect back to the source. This waste of signal radiation, produce side lobe and back lobes. The implication of a negative index, the radiated signal will travel backwards [6].

Metamaterials is artificial structures where the refractive index has a negative permittivity and permeability value over some frequency range. Metamaterials increase performance of antenna systems to launch energy into free space. This metamaterial does not occur in any know natural material, and it only can realize with modified the structure of material. It can also define as Left-Handed (LHM) material because of both the effective permittivity and permeability happen in the left side region [7]. Hence, permittivity can be found naturally in several metals such as gold and silver but permeability need to be engineered artificially to be negative [8].

In this study a Circular Shape Metamaterial Antenna with Defect Ground Structure DGS was introduced to investigate the effective negative permittivity and negative permeability. It is constructed by using circular shaped DGS where the ground plane of microstrip antenna is modified to reduce the shunt capacitance of the structure. Besides that, it is design to improve the performance of conventional antenna in term of directivity and return loss at frequency 5.4GHz. Rectangular patch antenna was used cooperated with the metamaterial structure to radiate the signal. The S-parameters from the result simulation used to determine the negative permittivity and permeability of the material structure.

II. DESIGN METHODOLOGY

A. Flow Chart

Fig.1 below shows the work flow in designing the microstrip patch antenna.

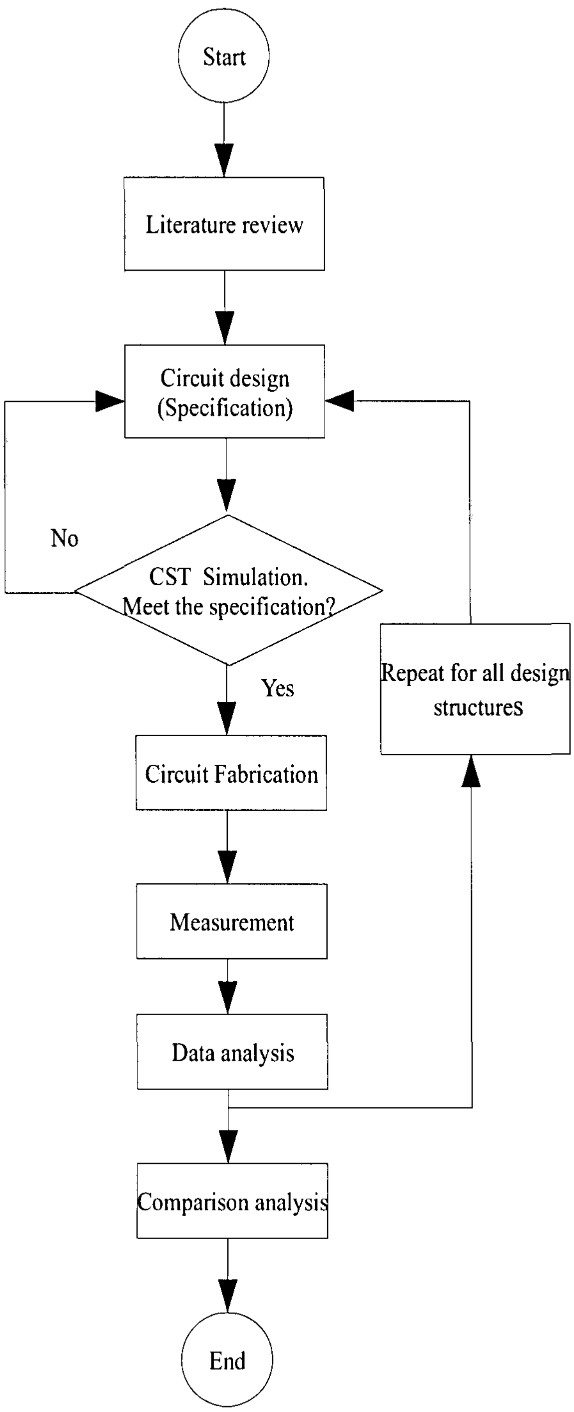

Fig. 1. Design methodology flowchart

B. Metamaterial Structure

The structure proposed in this study is shown in Fig.2. It was constructed by using circular shape Defect Ground Structure (DGS). In this design structure, RO3003 substrate with the circular shaped DGS was used to create the metamaterial features. The single unit cell of this structure was test by placed the 50ohm line above the substrate. The details properties of RO3003 substrate are shown in Table 1.

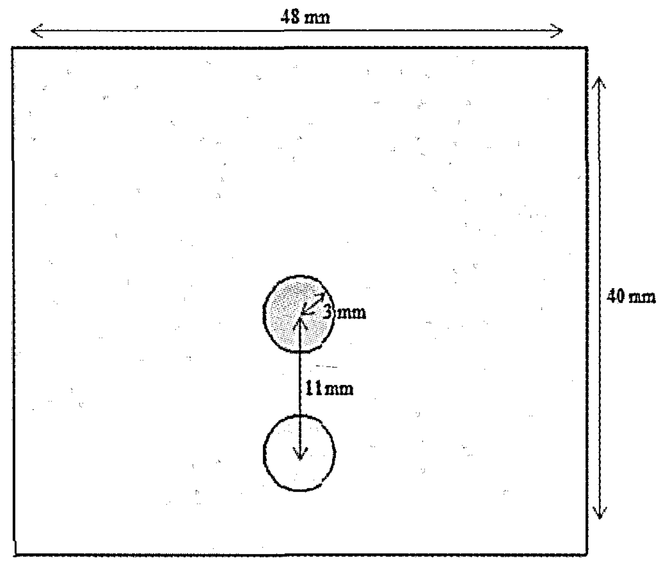

Fig. 2. Dimensions of the single unit cell construction

TABLE I
RO3003 SUBSTRATE PROPERTIES

Properties	Values
Permittivity,	3
Permeability,	1
Substrate Height, h	0.75mm
Thickness of Copper, t	0.035mm

The simulation of metamaterial structure in Fig.2 was performing by using Computer Simulation Technology (CST) Microwave Studio. From the simulation result, data in S parameter used to obtain the permittivity and permeability of circular shape DGS. The frequency of antenna it's depending on where the negative permittivity and permeability occur. There are several methods to verify the permittivity and permeability of a substrate that can be extracted from S-parameters. In this project, Nicolson-Ross-Weir (NRW) technique chosen to attain the permittivity and permeability since this technique is widely used to convert the S-parameters. In [9] the procedure and step by step proposed by NRW method were explained from the following equation;

$$\Gamma = X \pm \sqrt{X^2 - 1} \quad (1)$$

$$X = \frac{s_{11}^2 - s_{21}^2 + 1}{2 s_{11}} \quad (2)$$

$$T = \frac{s_{11} + s_{21} - \Gamma}{1 - (s_{11} + s_{21})\Gamma}. \quad (3)$$

Where,

Γ = reflection coefficient of the circuit
χ = correct root
T = transmission coefficient
S_{11} = reflected signal
S_{21} = transmitted signal

Both S_{11} and S_{21} were obtaining from simulation result of CST Microwave Studio. The magnitude value must be less than one in order to find the X which is in form of S-parameter.

$$\ln\left(\frac{1}{\mathrm{T}}\right) = \ln\left(\frac{1}{\mathrm{T}}\right) + j(\theta_{\mathrm{T}} + 2\pi n) \tag{4}$$

Where

$$n = \frac{L}{\lambda_g} \tag{5}$$

n = number of root (0, ±1, ±2…)
L = material length in cm
λ_g = wavelength in cm
θ_T = phase of transmission coefficient in radian

The value of n can be obtained by solving equation (6) and (7). Then the value of equation (7) is then substituted into (5). The value of n that was obtain from the calculation must be rounded up to the nearest integer to obtain the actual root number,

$$\frac{1}{\Lambda} = -\frac{1}{\lambda_o}\sqrt{\varepsilon_r^o \mu_r^o - \left(\frac{\lambda_o}{\lambda_c}\right)^2} \tag{6}$$

$$\left(\frac{1}{\Lambda}\right) = \frac{1}{\lambda_g} \tag{7}$$

Where Λ is a complex number of wavelength, ε_r is the initial guess of material permittivity, μ_r is the initial guess of permeability, λ_o is the wavelength in free space and λ_c is the cut-off wavelength. Equation (8) is obtained by substituting value from equation (4)

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2 \tag{8}$$

Then the permeability, μ_r and permittivity, ε_r can be solve by using the following equation,

$$\mu_r = \frac{1+\Gamma}{(1-\Gamma)\Lambda\sqrt{\frac{1}{\lambda_o^2} - \frac{1}{\lambda_c^2}}} \tag{9}$$

$$\varepsilon_r = \frac{\lambda_o^2}{\mu_r}\left[\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2\right] \tag{10}$$

C. *Rectangular Patch Antenna Design*

The design procedures of Conventional Rectangular Microstrip Patch Antenna consist of the several important parameters which is the operation frequency f_o, dielectric constant ε_r of the substrate and height h of dielectric substrate. The part of the conventional rectangular microstrip patch antenna is feeder line, radiation patch, ground and substrate. Radiation patch, feeder line and ground plane are made from copper, while the substrate is ROGER RO3003. The antenna was designed to operate at 5.4GHz.

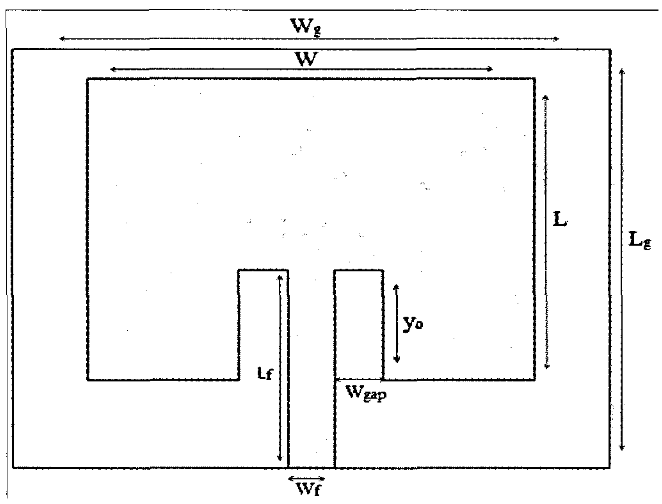

Fig. 3. Dimension of conventional patch antenna.

After all the parameters were selected, the next step is to calculate the dimension of the antenna. The following formula [10] is used to obtain the suitable parameter.

Step 1: calculation of width (W)

$$W = \frac{c}{2f\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{11}$$

With c is the free space velocity of light, f_o is the frequency of operation, ε_r is the dielectric constant and h is the height of the dielectric substrate.

Step 2: calculation of Effective Dielectric Coefficient

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} \quad (12)$$

Step 3: calculation of Effective Length

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{reff}}} \quad (13)$$

Step 4: calculation of length Extension

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)\left(\frac{w}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{w}{h} + 0.8\right)} \quad (14)$$

Step 5: calculation of actual Length of patch

$$L = L_{eff} \_ 2\Delta L \quad (15)$$

Step 6: calculation of Ground Dimensions

$$L_g = 6h + L \quad (16)$$

$$W_g = 6h + W \quad (17)$$

The design of a single rectangular patch antenna was done. The inset feed technique is being used to match the patch antenna using a feed line. This is the best feeding techniques and it is also easy to control the input impedance of the antenna. The input impedance level of the patch can be control by adjusting the length of the inset [11]. The following formula used to calculate the distance of y_o.

Step 7: calculated the conductance of the microstrip radiator, G_1.

$$\lambda_o = \frac{c}{f} \quad (18)$$

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_{reff}}} \quad (19)$$

$$G_1 = \frac{W}{120\lambda_o}\left[1 - \frac{1}{24}(k_o h)\right]^2 \quad (20)$$

Where,

$$k_o = \frac{2\pi}{\lambda_g} \quad (21)$$

Then, resonant input resistance, R_{in} can be calculated by using the following equation:

$$R_{in}(L = \ell) = \frac{1}{2G_1}\left(\cos^2\frac{\pi}{L}y_o\right) \quad (22)$$

After constructing the metamaterial structure, next step is to verify the negative permittivity and permeability of the material structure from the result simulation data by using the NRW formula. The operational of antenna, depends on the negative permittivity and permeability at desired frequency which is at 5.4GHz. After carry out this process, the microstrip antenna with the metamaterial can be designed. Furthermore an optimization process has been done to obtain the best performance in directivity and return loss. In order to maintain the impedance of the transmission line, the width of the transmission line was kept constant along the optimization process [12]. Table 2 shows the construction parameter of a conventional antenna and metamaterial antenna.

TABLE II
CALCULATED DIMENSION OF CONVENTIONAL PATCH ANTENNA AND METAMATERIAL ANTENNA

Description	Conventional antenna(mm)	Metameterial antenna(mm)
Patch Width, W	20.4	25.2
Patch Length, L	15.565	14.6
Substrate Width, W_g	24.2	48.0
Substrate Length, L_g	20.6	40.0
Feeder Width, W_f	1.901	1.901
Feeder Length, L_f	6.6975	16.2729
y_o	3.6	3.6

III. RESULT AND DISCUSSION

A. Simulation Result

Fig.4 and Fig.5 show the negative permittivity and permeability that was obtained from the metamaterial structure. In this project, at frequency 5.4GHz both permittivity and permeability were at negative value, therefore exhibits the metamaterial properties.

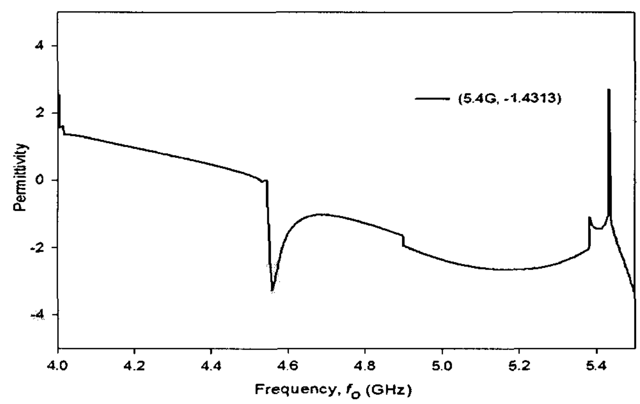

Fig.4: The permittivity of metamaterial structure

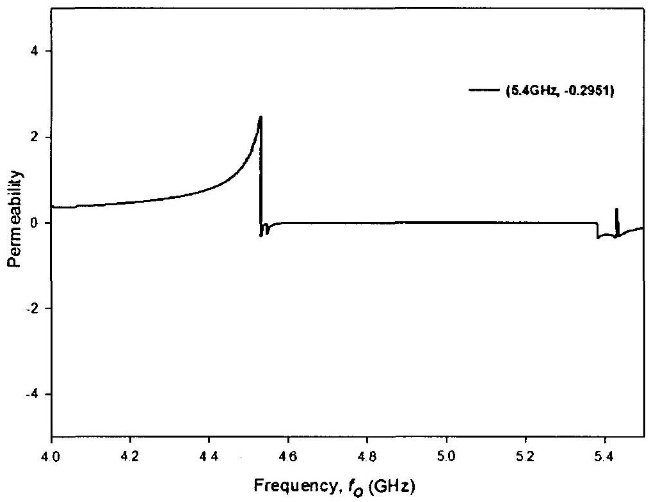

Fig. 5. The permeability of metamaterial structure

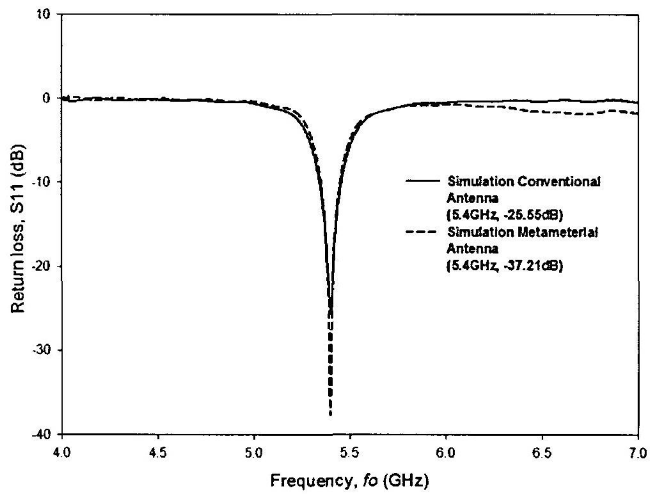

Fig. 6. Measurement result of S_{11} parameter between conventional antenna and metamaterial antenna

In Fig.6, the simulation result of S_{11} parameter between conventional antenna and metameterial antenna are -25.55dB and -37.21dB respectively. It shown that the return loss value of metameterial antenna is higher compare to the conventional antenna. The conventional antenna produced acceptable level of return loss, however metameterial antenna performs better than conventional antenna. The high value of return loss mean that the amount of radiated signal by antenna is much higher and very small reflection signal back to the source. Futhermore it also has the filtering characteristics which is reject the unwanted signal and avoid the inteference with the another signal [13]. Meanwhile the bandwitdh of conventional antenna is 111MHz which is 10.81% higher than metamaterial antenna. Although the metameterial antenna has smaller bandwidth, it has good return loss, therefore it is suitable to be used for narrowband application.

Fig.7 and Fig.8 show the directivity gain for the conventional antenna and metameterial antenna. The directivity gain of the metameterial antenna is 7.99dBi which is much higher than conventional antenna (6.65dBi). In metameterial structure, which using the concept of negative index refraction, the signal radiated by the antenna was propagated in opposite direction and this will increase the performance of antenna in terms of directivity. The implementation of negative index refraction will reduce the wasted signal in antenna system. The higher directivity means that more signal will propagate at a particular direction. Thus shows the metameterial structure acts as a focusing device where the beam become narrower and the directivity is increased [14].

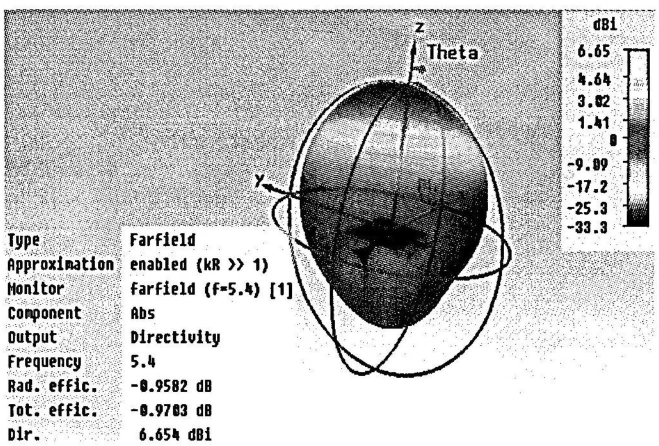

Fig. 7. Directivity gain of conventional antenna

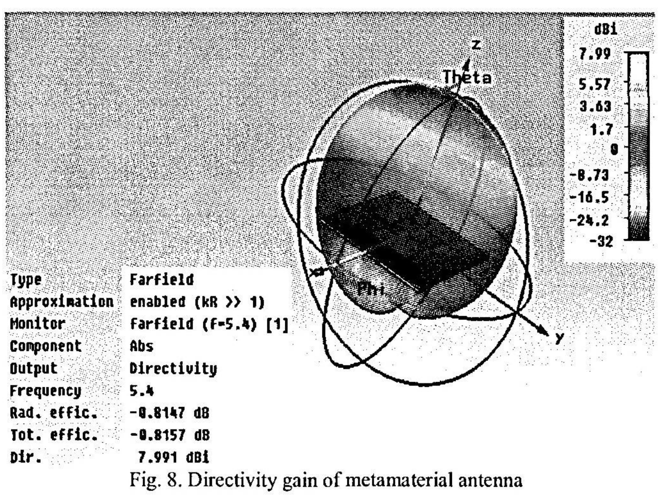

Fig. 8. Directivity gain of metamaterial antenna

B. Measurement Result

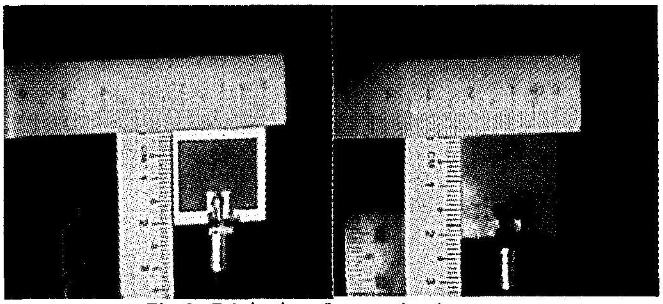

Fig. 9. Fabrication of conventional antenna

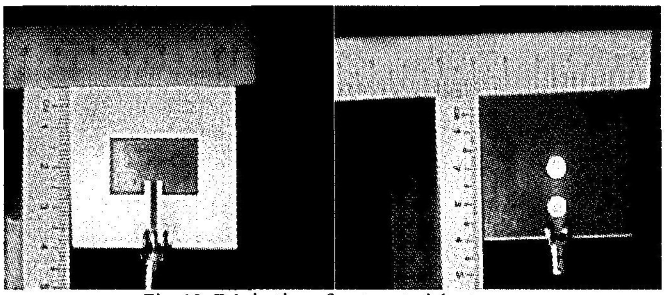

Fig. 10. Fabrication of metamaterial antenna

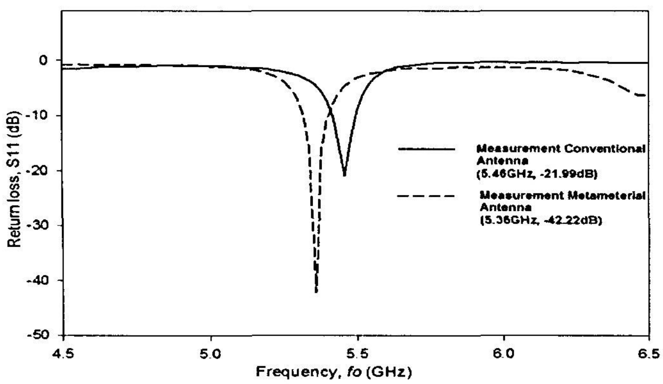

Fig. 11. Measurement result of S_{11} parameter between conventional antenna and metameterial antenna

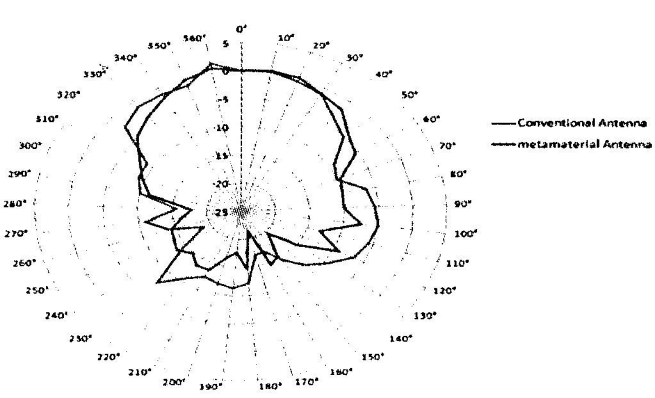

Fig. 12. Measurement result of radiation pattern between conventional antenna and metamaterial antenna

Fig.9 and Fig.10 show the fabricated conventional microstrip antenna and metameterial antenna respectively. In Fig.11, the measurement result for the return loss is presented. The return loss, S_{11} for conventional antenna is 21.99dB at frequeancy 5.46GHz. It shows that the frequency shifted to the right from the original frequency (5.4GHz). Meanwhile the return loss for metamaterial antenna has been shifted to the left about 42.42dB at frequency 5.36GHz. It is because of the error during fabrication process or losses along the VNA cable. The bandwidth of the metamaterial antenna is 80MHz which is much wider than the conventional antenna which is 60MHz. Table 3 shows the summarized of the simulation result and measurement result.

TABLE III

COMPARISON BETWEEN SIMULATED AND MEASUREMENT OF CONVENTIONAL ANTENNA AND METAMATERIAL ANTENNA.

Antenna parameter	Simulation		Measurement	
	Conventional Antenna at (5.4GHz)	Metamaterial Antenna at (5.4GHz)	Conventional Antenna at (5.46GHz)	Metamaterial Antenna at (5.36GHz)
Return loss S_{11}	-25.55dB	-37.21dB	-21.99dB	-42.22dB
Directivity	6.65dBi	7.99dBi		
Bandwidth	111MHz	99MHz	60MHz	80MHz

In previous research work [15], the combination of the square rectangular Split Ring Resonator (SRR) and the capacitance loaded Strip (CLS) were used to obtain the negative value of permittivity and permeability. The metamaterial structure act as reflector was incorporation with a single patch microstrip antenna operated at frequency 2.4GHz. the result of S_{11} and directivity gain are shown in table 4.

In Table 4, the proposed antenna produce a better return loss S_{11} compare to SRR structure. The signal radiated by circular shape DGS antenna is higher than signal travel back to the source. Meanwhile SRR structure offer a good directivity than the circular Shape DGS. The signal travel from the SRR structure incorporated with the patch antenna is more sharp at a particular direction. In term of bandwidth SRR antenna provide a larger bandwidth. Thus it can cover larger area. Therefore circular shape DGS is suitable to cover small place area since it has a narrow bandwidth.

TABLE IV

COMPARISON AMONG DIFFERENT METAMATERIAL STRUCTURE

Parameter antenna	Split Ring Resonator	Circular Shape DGS
Return loss, S_{11}	-10dB	-37.21dB
Directivity	Improve 4.22dBi	Improve 1.34dBi
Bandwidth	Improve 4%	Decrease 10.81%
Overall dimensions	117mm x 127mm x41.6mm	40mm x 48mm x 0.75mm

IV. CONCLUSION

As a conclusion, the Circular Shape Metameterial Antenna with Defect Ground Structure (DGS) has been successfully designed and fabricated. The circular shape DGS structure is able to produce the metamaterial features. By using this metamaterial antenna, the signal propagated become more sharp and it was enhancing the performance of the conventional antenna in term of directivity and return loss about 20.15% and 45.3%. This metamaterial antenna it's suitable for Wireless LAN application to cover a small area since it has the narrowband application because it have a smaller bandwidth and high directivity.

V. FUTURE RECOMMENDATION

In the designing of the metamaterial antenna, there are several improvements to enhance the directivity and reducing the size of the metameterial antenna can be taken into consideration for future research. Furthermore the different substrate, structure, type of patches and feeding techniques may also affect the performance of antennas.

VI. ACKNOWLEDGMENT

The author would like to show gratefulness to Pn. Robi'atun Adayiah Binti Awang, Dr. Ahmad Asari Sulaiman and the team of lecturer that guide me from the beginning to the end of the projects. Special thanks to all group member for supporting and shared the knowledge during to make this project.

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