# Circular Patch Antenna Using Metamaterial

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***Abstract-*** This paper recommends a new technique of constructing circular antenna using metamaterial substrate. The study is concentrating on C-band frequency at 4.7GHz. The new small antenna has improved the performances in terms of directivity, gain, return loss and size. The size of metamaterial antenna is decreased by a factor 2.4. The directivity is increased from 4.17 for conventional antenna to 5.66 for metamaterial antenna. Better return loss also displayed from metamaterial antenna which is -24.2 dB. By analyzing the radiation pattern, the metamaterial antenna also focus to the supposed location. Result from the combination of material and structure on a single cell was led to the material with negative permittivity or metamaterial. The compact antenna is expected to improve features of conventional design by reducing the cost of production in correlation to the size reduction in mess production.

## I. INTRODUCTION

One of the remarkable aspects of the human civilization development is the intention to create or construct something that is not available in natural [1]. Metamaterial is one of thing that does not exist in the nature [2]. The invention of metamaterial is started in the late 1960s, Veselgo studied the electrodynamics of substances with simultaneously negative values of dielectric permittivity and magnetic permeability[1, 3]. The material with negative permittivity and permeability also know in several name such as left-handed material (LHM) and backward wave material (BWM) [4]. Although metamaterial not present in nature, interesting properties were theoretically predicted for these substances, such as the reversal of the Snell Law, Doppler Effects, Cherenkov radiation and built perfect lenses [3]. Several works have been aimed towords the improvement of the performances of antennas in the microwave frequency range. Antenna can be defined as part of a transmitting or receiving system which is designed to radiate or to receive electromagnetic waves [5]. The applying of metamaterial in the antenna hopefully will improve the performance of the antenna.

This paper will focus on invention of circular patch antenna using metamaterial. The properties of metamaterial structure and radiation characteristics of the circular patch antenna are also been investigated. This study show that by applying the metamaterial into the antenna as a substrate, several positive result has been appears such as smaller in size, better directivity, and also improving the gain direction.

## II. METHODOLOGY

The initial stage of constructing the metamaterial antenna was done by building the single unit of metamaterial with choosing the possible structure that can produce metamaterial. The commonly known structures are split ring structure, symmetrical-ring structure, S-structure and omega structure[6]. This study took the split ring structure as it uses a single unit cell to obtain metamaterial. Split ring structure was chosen because it is a simple structure and a common structural used in producing metamaterial. The dimension of the split ring structure is shown as below:

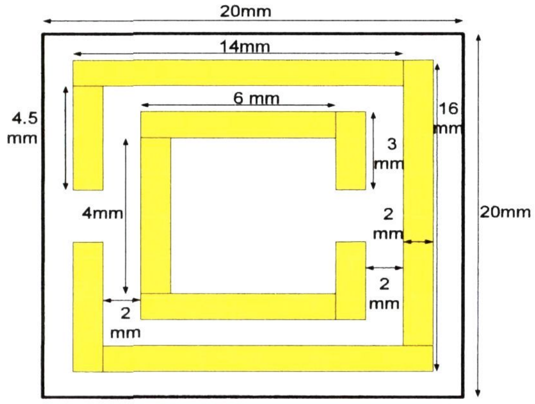

Figure 1: A dimension of one unit cell metamaterial structure

The single unit cell of metamaterial consists of two parts namely as substrate and structure. The substrate that was used in this paper was Flame Retardant 4 (FR-4) while for the structure a perfect Copper was used. FR-4 material and copper were used because they are the common material used in order to produce metamaterial. The details about FR-4 are shown in table below

TABLE I
FR-4 SUBSTRATE PROPERTIES

| | |
|---|---|
| Permittivity, ε | 4.9 |
| Loss Tangent | 0.025 |
| Permeability, μ | 1 |
| Substrate Height, h | 0.25mm |

Computer Simulation Technology (CST) Microwave Studio was used to build the split ring structural and then simulated using this software. As shown in Fig. 1, the waveguides ports are located at the X-axis where the ports act as the source of the wave to enter into metamaterial. Prefect Electrical conductor (PEC) was applied at the top and bottom of Y-axis. In lieu of that, Perfect Magnetic Conductor (PMC) boundary condition was placed at the front and back of Z-axis. As a result from this simulation, the s-data were collected to verify the permittivity of the material and whether the material is metamaterial.

The next step to construct the metamaterial antenna is to verify the permittivity. There are several methods to verify the permittivity. The four popular methods are Nicolson-Ross-Weir (NRW), NIST iterative technique, new non-iterative technique and short circuit technique [7]. All the methods mentioned are based upon the S-data that were collected previously from the CST microwave studio simulation and then are converted to obtain permittivity and permeability.

This paper chose Nicolson-Ross-Weir (NRW) technique to attain the permittivity and permeability because it is the most regular technique that is used widely to convert S-data to permittivity and permeability [7]. Moreover, this method provides an easy and simple calculation to obtain permittivity and permeability.

$S_{11}$and $S_{21}$ were obtained from the CST microwave studio are used to calculate the reflection coefficient using the NRW method

Reflection Coefficient

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

where

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

As a step to acquire the correct root (x) which is now in the form of S-parameter, the magnitude of the reflection coefficient (|Γ|) must be less than one. The following stage is to calculate the transmission coefficient of the metamaterial.

Transmission Coefficient

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

$$In\left(\frac{1}{T}\right) = In\left(\frac{1}{T}\right) + j(\theta_T + 2\pi n) \quad (4)$$

where

$$n = \frac{L}{\lambda_g} \quad (5)$$

Where

$n$ = number of roots $(0, \pm 1, \pm 2, \ldots\ldots)$
$L$ = material length in cm
$\lambda_g$ = wavelength in sample in cm
$\theta_T$ = phase of transmission coefficient in radian

The value of *n* can be clarified by applying equation (6) and equation (7) below. Then the value of equation (7) applied into equation (5). The value of *n* that was obtain must be rounded up to the nearest integer to get the actual number of roots

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

where

$\Lambda$ = complex wavelength
$\varepsilon_r$ = initial guess of material permittivity
$\mu_r$ = initial guess of material permeability
$\lambda_o$ = wavelength in free space
$\lambda_c$ = cut-off wavelength

$$\Re e\left(\frac{1}{\lambda}\right) = \frac{1}{\lambda_g} \quad (7)$$

By substituting value from equation (4), equation (8) has been obtained

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

By applying value from equation (1) and equation (6) into equation (9), the permeability value of the metamaterial has been obtained.
Permeability

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

By substituting the value from equation (8) and equation (9) into equation (10), the permittivity value of the metamaterial has been obtained

Permittivity

$$\varepsilon_r = \frac{{\lambda_o}^2}{\mu_r}\left(\frac{1}{{\lambda_c}^2} + \frac{1}{\Lambda^2}\right) \tag{10}$$

The formula of NRW technique is constructed using MATLAB R2007b software as an effort to get the value of permittivity in graphical forms. The graph of permittivity value of metamaterial versus frequency was also plotted using this software to get a lucid figure of the negative permittivity.

The subsequent step to construct the metamaterial antenna is the construction of a conventional antenna. There are many conventional antenna exist. As for that, the conventional circular patch antenna was chosen as a case study to compare its performance with metamaterial circular patch antenna. The conventional circular patch antenna consists of feeder line, patch, ground and substrate. The circular patch antenna was illustrated in figure below:

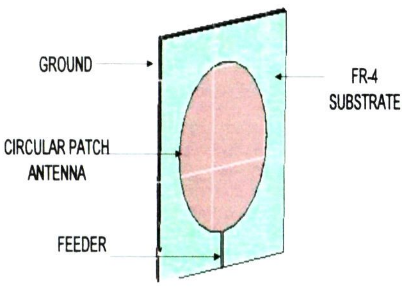

Figure 2: A view of conventional circular patch antenna

The antenna that has been designed for this paper operates at 4.7GHz. Copper material was used for the patch and transmission line. PEC material is used for the ground while for the substrate a FR-4 material is used. Initial dimension for the antenna was calculated by using simple formulae of an antenna design [8]. The initial radius value that has been calculated will facilitate to achieve the desire result. This can reduced the time consumption during optimization process.

Patch Radius

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \tag{11}$$

Where

h = height of substrate in cm
$\varepsilon_r$ = permittivity of material used.

$$F = \frac{8.791\ x\ 10^9}{f_r\sqrt{\varepsilon_r}} \tag{12}$$

Where

$f_r$ = resonant frequency
$\epsilon_r$ = permittivity of material used.

From the formula above, the radius of circular patch antenna can be determined. It will be applied at 4.7 GHz operating frequency. For the width and length of the transmission line, their values can get from line calc software. All the details of the parameter are shown in the table below:

TABLE II
CONVENTIONAL ANTENNA PARAMETERS

| Parameter of antenna | Length of parameter |
|---|---|
| Radius,a | 16mm |
| Width of transmission line | 0.845mm |
| Length of transmission line | 8.419mm |

The performances of the antenna were observed again in CST Microwave studio. Therefore, all the parameters were implemented in the CST microwave studio to design an antenna and simulated to achieve the desired performance.

The final stage of executing this study is to construct a metamaterial antenna. The difference of metamaterial antenna with the conventional antenna is that the substrate and size differ. FR-4 substrate will be replaced with single unit cell metamaterial substrate. Given that the single unit cell substrate is smaller than the conventional antenna, the size of antenna will be lessened by ratio and pursue the single unit cell metamaterial dimension. Consequently, the size of metamaterial antenna is smaller than the size of a conventional antenna. The figure of metamaterial antenna is shown below:

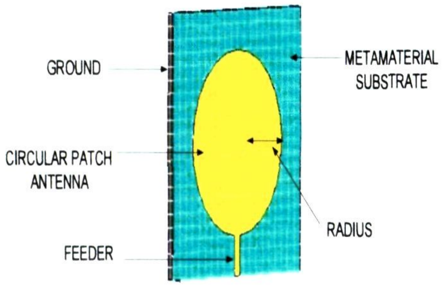

Figure 3: A view of metamaterial circular patch antenna

On top of getting the desire output, the optimization process was performed in CST microwave studio. In order to maintain the impedance of the transmission line, the width of the transmission line was kept constant. The other parameters such as radius and transmission line's length, they were continuously varied until achieving the yearning result. As for the operating frequency for the metamaterial antenna, it was maintained at 4.7GHz.

All the metrology step above was summarize in the flow chart below:

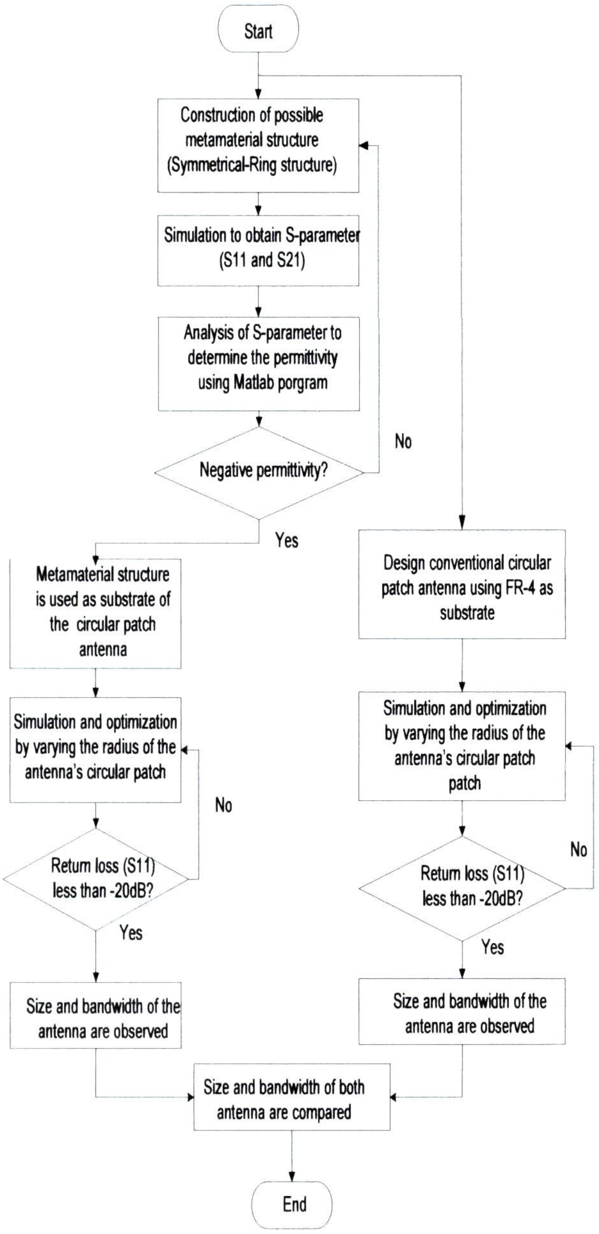

Figure 4: Flow chart of constructing conventional antenna and metamaterial antenna

## III. RESULT AND DISCUSSION

Figure below illustrates the response of one unit cell split ring metamaterial construction. One unit cell that was constructed in CST microwave studio has been simulated and the S-data were imported into MATLAB R2007b program which contains NRW conversion technique formulae to convert S-data to permittivity. As a result, negative permittivity appears at a frequency between 4.6GHz to 4.9GHz as shown in the figure. Therefore an antenna that will use this material as the respective substrate must be constructed at that range of frequency. Hence, the frequency used is 4.7GHz with permittivity -3.09

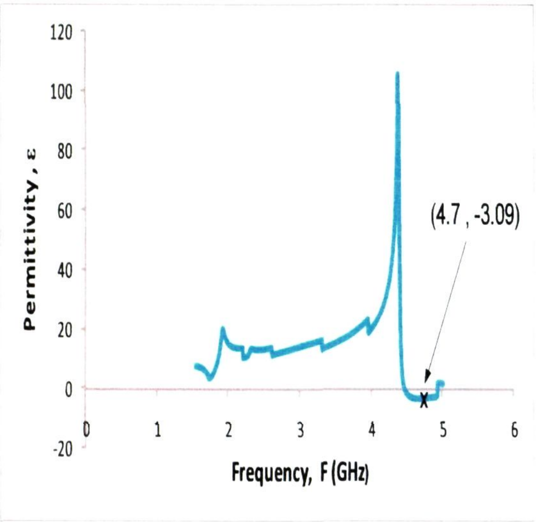

Figure 5: Permittivity of one unit cell split ring structure

The metamaterial that has been produced was applied in an antenna as a substrate. Simultaneously, conventional antenna was constructed to do a comparison of performance between both antennas. After simulation, it has shown that the metamaterial antenna performance is better compared to the conventional antenna. This results in several parameters. Firstly, the size of metamaterial was smaller than the conventional antenna. It was smaller by 2.4 in ratio which is about 41.667%. It can be said that the new antenna produced was twice smaller compared to the conventional antenna. The size of both antennas is shown in table below.

TABLE 3
COMPARISON OF SIZE BETWEEN METAMATERIAL ANTENNA AND CONVENTIONAL SNTENNA

| Description | Conventional antenna | Metamaterial antenna |
|---|---|---|
| Radius | 16.9 mm | 7.0035 mm |
| Substrate width | 48 mm | 20 mm |
| Substrate length | 48 mm | 20 mm |
| Transmission line width | 0.845 mm | 0.845 mm |
| Transmission line length | 9.125 mm | 4 mm |

The following parameter that can be observed was the return loss. Figure below gives an idea about the return loss for both antennas after optimization process. The return losses for both antennas were less than -20 dB. But the metamaterial antenna produced much smaller value which is -24.2 dB compared to the conventional antenna which is about -22.08 dB. The difference of return losses between both antennas was around 2.12 dB. This value can be considered as good because the value of a return loss must be small. A small return loss is necessary to minimize the reflection wave back to the antenna since the reflection power is capable of damaging the microstrip patch antenna. The small value also shows that the antenna operates at the utmost performance.

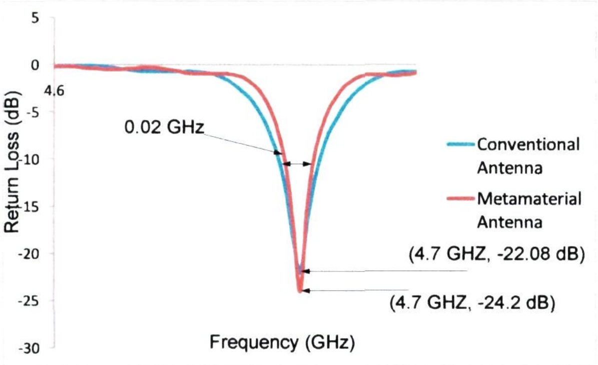

Figure 6: Return loss of conventional circular patch antenna and Return loss of metamaterial circular patch antenna

The graph also represents the bandwidth for both antennas. Bandwidths for both antennas were same which was 0.02GHz. This bandwidth cannot be considered as broad bandwidth because the antenna was designed to be only suitable for narrow bandwidth.

Apart from that, another parameter that can be analyzed was the directivity of both antennas. The directivity of the metamaterial antenna is better and higher compared to the conventional antenna as shown in figure below. The directivity for metamaterial antenna was 5.656 dBi while the conventional antenna's directivity was around 4.170 dBi. The difference was around 1.486 dBi. The performance also can be evaluated from the radiation pattern whereby the radiation pattern for metamaterial radiates $90^0$ from the plane, noted that the antenna was design at the XY-plane. It shows that the antenna has radiated directly to the supposed location.

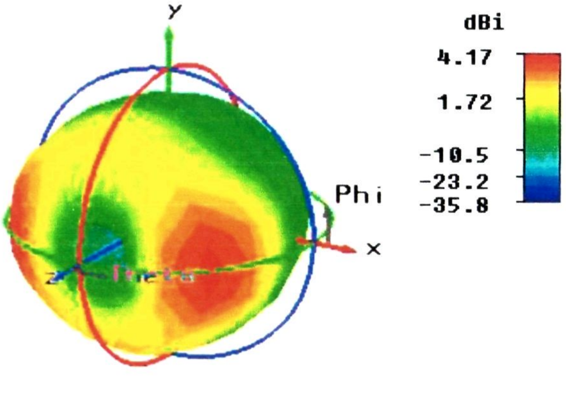

Figure 7: Directivity of conventional circular patch antenna

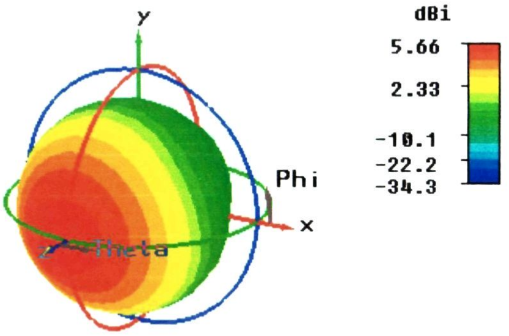

Figure 8: Directivity of metamaterial circular patch antenna

Last but not least, the final parameter that can be observed was the gain of the antenna. The conventional antenna's gain is higher compare to the metamaterial antenna. The gain for conventional antenna was approximately 8.061dB while for metamaterial antenna the gain was around 1.986dB. Although there is a large difference between both gains, the conventional antenna's gain was scattered and did not radiated directly to the supposed coordinate. On the contrary, with the usage of metamaterial antenna, it can recover this weakness by helping the conventional antenna to radiate to the desired coordinate. These situations were shown in figure below:

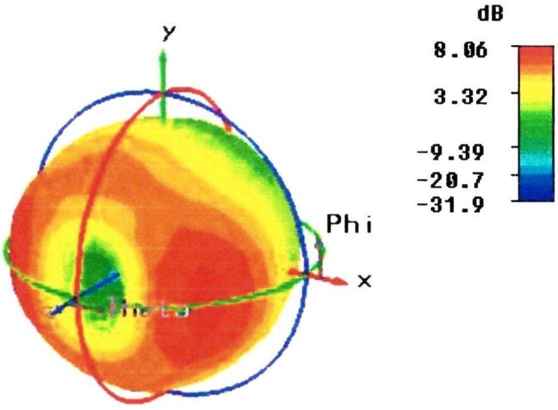

Figure 9: Gain of conventional circular patch antenna

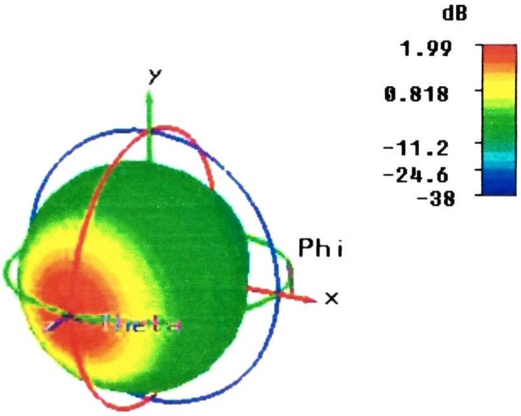

Figure 10: Gain of metamaterial circular patch antenna

## IV. CONCLUSION

It can be seen throughout this paper that metamaterial has successfully proven by having negative permittivity at certain range of frequency. For split ring structure the negative permittivity at frequency 4.6 GHz to 4.9 GHz

By using the metamaterial as a substrate of the antenna, the improvement that can be seen is the reducing size of antenna by factor of 2.4. The improvement in return loss value which is -24.2 dB. The bandwidth of metamaterial also maintain at 0.02 GHz. Lastly the metamaterial antenna radiated towards desire location

## V. FUTURE DEVELOPMENT

It is recommended that, several factors need to be considered for further research. First and foremost, the method to determine the metamaterial of one unit cell needs to be reviewed. There are several methods that are much accurate compared to the Nicolson-Ross-Weir (NRW) method such as NIST iterative technique, new non-iterative technique and short circuit technique. With the implementation of different techniques, a greater comparison can be made to achieve a better result. Next, the consumption of materials to produce metamaterial should vary and not focusing on using flame retardant 4 (FR-4) only. The variety of materials used may lead to improvement in results or even to declining results. This is a risk worth to be taken as it may produce a new invention in this area. Last of all, the implementation of different structure of patch and also the type of feeding should be made to attain a much constructive result. It is also necessary to make the metamaterial be implemented in various fields.

## VI. ACKNOWLEDGEMENT

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