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Circular Patch Antenna on Metamaterial

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Abstract

This paper recommends a compact circular patch antenna on metamaterial substrate for C-band applications. The antenna is designed for some improvement in the performance of directivity gain, return loss and size of circuit area. The size of the new metamaterial antenna has been reduced by a factor of 2.4 and the directivity gain was increasing from 4.17 dBi in conventional design on Flame Retardant 4 (FR-4) to 5.66 dBi in the new approach. A better return loss was obtained from the metamaterial antenna which is -24.2 dB compared to -22.08 from the conventional antenna. By analyzing the radiation pattern, the metamaterial antenna has a sharp focus to the targeted direction. The compact antenna is expected to improve the cost of production due to the size reduction in the overall circuit area especially in a mess production.

Keywords: Circular patch antenna; matematerial; split-ring structure.

1. Introduction

One of the remarkable aspects of the human civilization development is the intention to create something that is not available in natural [1]. Metamaterial is a substrate that does not exist independently in the nature [2]. The invention of metamaterial was started in the late 1960s, Veselago has 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 known in several name such as left-handed material (LHM) and backward wave material (BWM) [4]. Although metamaterial does 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 done aim towards the improvement of the performance of antennas in the microwave applications.

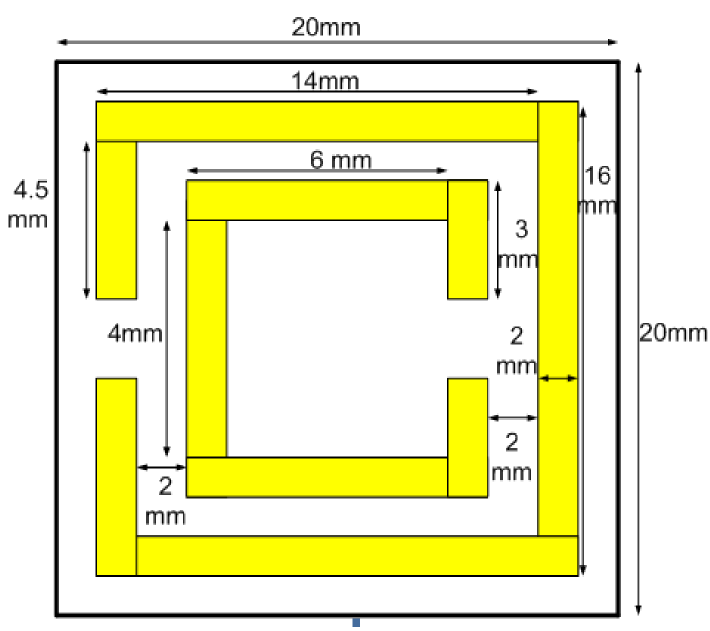
The first structure that has been used to prove the existing of metamaterial was a split ring structure invented in 2001 by Shelby Smith and Schultz at the University of California [5]. Three new structures were proposed in year 2005, starting with symmetrical ring structure than omega structure and the latest was S structure [6]. The implementation of metamaterial in microwave is expected to improve the performances of the devices since the material loss is dominant at the radio frequency applications.

This paper will focus on invention of circular patch antenna on a single cell of metamaterial. The properties of metamaterial structure and radiation characteristics of the circular patch antenna also have been investigated in this project.

2. Methodology

At the early stage of constructing the antenna on a new substrate, a single unit of metamaterial is needed to be constructed. The common structures to build the material are split ring, symmetrical-ring, S and omega structures [7]. This study will investigate on the split ring structure since the architecture is only uses a single unit cell to obtain the left-handed material features. This structure was chosen due to the simple assembly construction. The dimensions of the split ring structure are shown in the Figure 1.

Figure 1: Dimensions of the single unit cell construction



The single unit cell substrate is containing of FR-4 and the conductor structures which were constructed from copper. The details properties of FR-4 are shown in Table 1.

Table 1: FR-4 substrate properties

Properties	**Values**
Permittivity, ε	4.9
Loss Tangent	0.025
Permeability, μ	1
Substrate Height, h	0.25 mm

Computer Simulation Technology (CST) Microwave Studio was used to simulate the circuit that shown in the Figure 1. From the simulation results, all S-parameters data were collected and analyzed in order to verify the permittivity of the new material result from the combination of FR-4 and rectangular split ring structures.

There are several methods to verify the permittivity and permeability of a substrate that can be extracted from S-parameters. The most four popular methods are Nicolson-Ross-Weir (NRW), NIST iterative technique, new non-iterative technique and short circuit technique [8]. All methods are based on the S-parameters that obtained from the simulation or measurement results.

In this project, Nicolson-Ross-Weir (NRW) technique was chosen to attain the permittivity and permeability since this technique is widely used to convert the S-parameters. Moreover, this approach provides an easy and simple calculation method. The equations were presented in [8] and step by step in this paper.

The values of $S_{11}$and S_{21} those obtained from the CST microwave studio were used to calculate the reflection coefficient using the NRW method. The reflection coefficient, Γ

$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{1}$$

where

$$X = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}} \tag{2}$$

As a step to acquire the correct root, *X* is must be in the form of S-parameter, the magnitude of the reflection coefficient, $|\Gamma|$ must be less than one. The following stage is to calculate the transmission coefficient of the metamaterial.

Transmission Coefficient

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

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

where

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

where

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

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

where

ε_r = initial guess permittivity
μ_r = initial guess permeability
λ_0 = free space wavelength
λ_c = cut-off wavelength

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

By substituting value from equation (4), equation (8) can be obtained

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

Applying values from equation (1) and equation (6) into equation (9), the permeability value of the metamaterial can be achieved.

$$\mu_r = \frac{1+\Gamma}{\Lambda(1-\Gamma)\sqrt{\frac{1}{\lambda_0^2}-\frac{1}{\lambda_c^2}}} \quad (9)$$

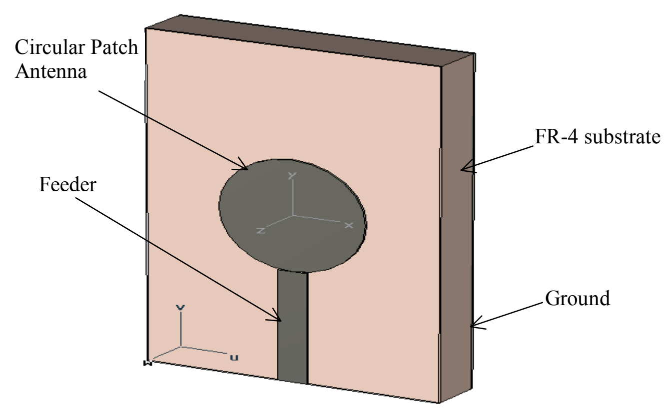
Substituting the values from equation (8) and equation (9) into equation (10), the permittivity value of the metamaterial can be acquired.

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2}+\frac{1}{\Lambda^2}\right) \quad (10)$$

These equations were applied in MATLAB R2007b software as an effort to get the value of permittivity in graphical forms. The graph of metamaterial versus frequency then was plotted to get a lucid figure of the negative permittivity.

A circular patch antenna was chosen as a case study for antenna performance comparison. One will be designed on FR-4 and another one is on metamaterial substrate. The patch antenna on FR-4 is illustrated in Figure 2.

Figure 2: A view of circular patch antenna on FR-4 substrate.



Copper metal was used to build up the patch and transmission line structures, while a perfect electrical conductor (PEC) as ground plane and FR-4 is considered as the base substrate. All antenna dimensions were calculated using standard formulae such as introduce in [9]. The radius of the circular patch is the main parameter that will facilitates to achieve the desire resonant frequency.

The antenna is designed to operate in C-band spectrum at 4.7 GHz for defense and security applications. The width and length of the transmission line values can be obtained from *linecalc* program which is available in *Libra* simulator software. All parameters are shown in the Table 2.

The initial length of radius was calculated approximately to achieve the desire antenna objectives. This approach is able to minimize the time consumption during optimization process.

Patch Radius

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

where

h = height of substrate (cm)

ε_r = permittivity of the material.

$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}}$

f_r = resonant frequency

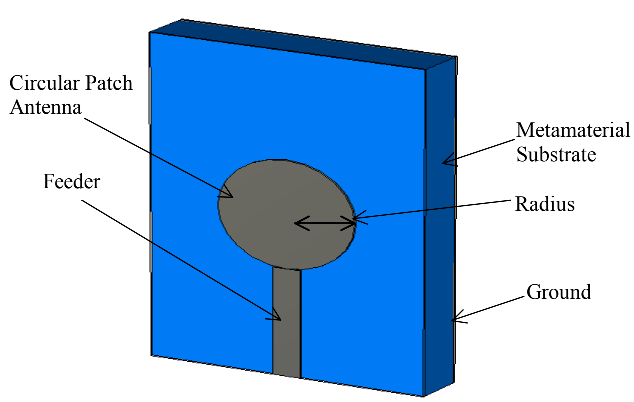
After constructing the rectangular split ring, a full simulation process will be done in order to obtain S-parameters. A confirmation on the matamaterial substrate is depending on the negative permittivity at the desired frequency that obtained from the calculation before a circular patch antenna will be designed on the new substrate. The difference between antenna on metamaterial and on FR-4 substrates is the size of overall layout. In the new approach, the FR-4 substrate was replaced by a single unit cell of metamaterial substance. The overall size of the conventional antenna will be reduced pursue to the single unit cell metamaterial layout. Consequently, the size of metamaterial antenna is smaller than the size of the conventional antenna on FR-4 substrate. Figure 3 shows the construction of the antenna on metamaterial substrate.

Table 2: Conventional antenna parameters

Parameter of antenna	**Length (mm)**
Radius, a	16.000
Transmission line width, W	0.845
Transmission line length, L	8.419

Besides getting the desire 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 was kept constant along the optimization process. The other parameters such as radius and the length of transmission line were continuously varied until achieving the yearning results.

Figure 3: A view of circular patch antenna on metamaterial substrate.

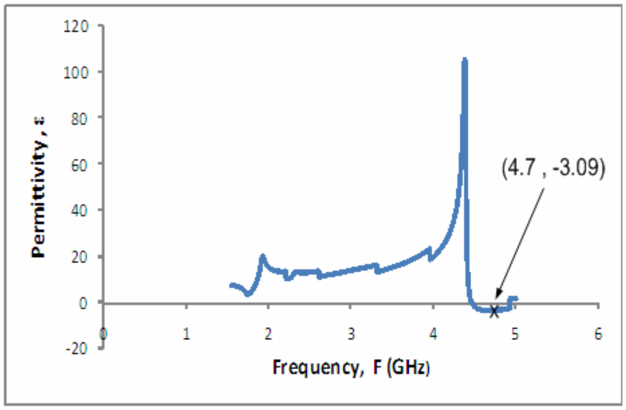


3. Results and Discussion

After the single unit cell was constructed in CST microwave studio, the simulated results were imported into MATLAB R2007b program. This tool contains NRW conversion formulae which is able to translate the parameters into permittivity. Figure 4 illustrates the result that was obtained from the conversion process. The negative permittivity appears in the range of frequencies between 4.6 GHz to

4.9 GHz. Therefore the antenna on metamaterial must be designed to operate within the range of frequencies. Hence, in this project, the frequency of 4.7 GHz was chosen since the permittivity is equal to -3.09.

Figure 4: Permittivity of the substrate from the conversion MATLAB software



The material that has been confirmed by the feature of LHM from the values of negative permittivity then was applied to the antenna design as a base substrate. Since the size and structure of the split ring is could not varied in order to maintain the features of left-handed material. The circular patch antenna on the metamaterial should only be designed for the limited size of the single unit cell. This approach is able to reduce the circular patch antenna but still able to operate at the same resonant frequency. Simultaneously, a conventional antenna was constructed on FR-4 for the purpose of comparison and analysis.

After both antennas have been simulated, the overall results prove that the antenna on metamaterial has better performances compared to the design on FR-4. The metamaterial antenna is able to reduce the size by the factor of 2.4 in ratio which is about 41.667%. In other word, the size of the new antenna is almost half of the design on FR4. A clear size reduction is shown in Table 3 for an obvious comparison.

Table 3: Size of antennas on FR-4 and metamaterial substrates

Description	**FR4 (mm)**	**Metamaterial (mm)**
Radius	16.90	7.00
Substrate width	48.00	20.00
Substrate length	48.00	20.00
Transmission line width	0.845	0.845
Transmission line length	9.125	4.00

Figure 5 shows the best value of return loss from both antennas after optimization. Both of the results are not less than -20 dB. However, the metamaterial antenna able to produce value of return loss at the resonant point of -24.2 dB compared to the antenna on FR-4 which is only about -22.08 dB. The smallest value of the return loss is required in order to minimize the reflection wave and simultaneously able to maximize the transmitting power. It means that the antenna is having a better performance. Moreover, this graph also represents the bandwidth of the antennas. The bandwidths from both antennas are about 200 MHz. These antennas ware designed for a narrow bandwidth system since the purpose of the application is for security and defense.

Figure 5: Comparison of return losses from the circular patch antenna on FR4 and metamaterial substrates

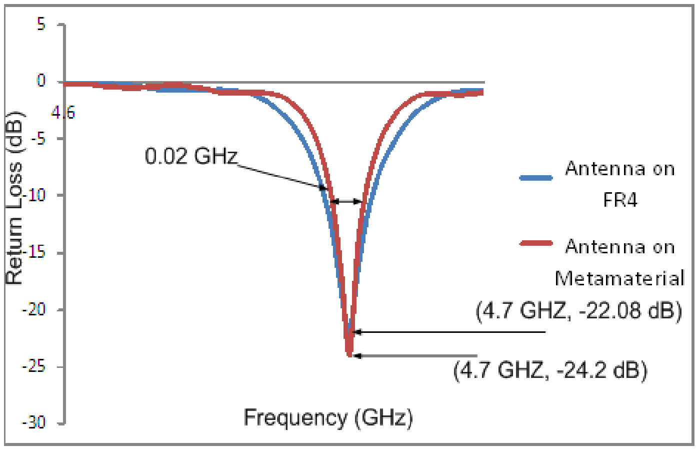


Figure 6: Directivity gain of the patch antenna on FR-4

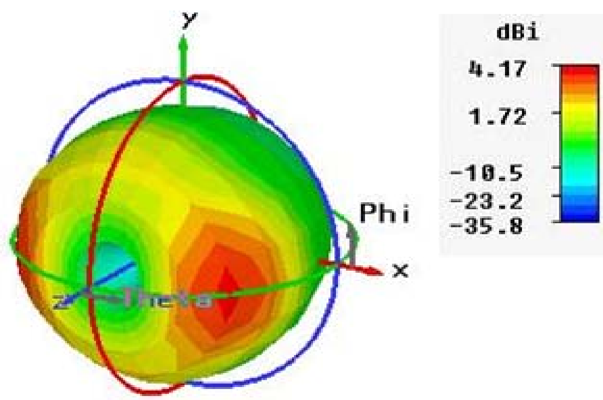
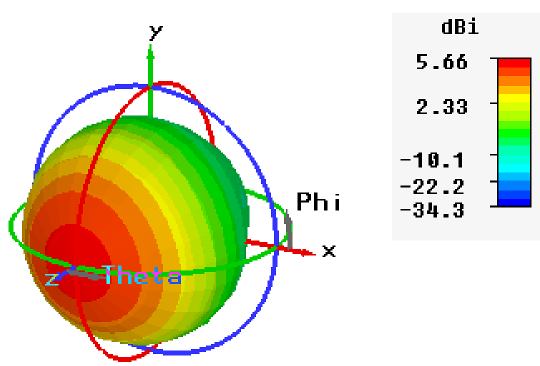


Figure 7: Directivity gain of the patch antenna on metamaterial



The directivity gain from the design on metamaterial is higher than the antenna on FR4 such as shown in Figure 6 and 7. The highest value of directivity gain obtained from the metamaterial antenna was 5.66 dBi while from the FR-4 was only around 4.17 dBi. The radiation pattern from the antenna on metamaterial was 90º from the XY-plane. It shows that the radiation direction was focused to the Z-axis where the targeted bearing is located.

The overall antenna gain can be observed from Figure 8 and 9. The antenna on RF-4 shows that the overall gain is about 8.06 dB which is higher than the antenna on metamaterial which is only around 1.99 dB. Although there is a great gain difference between both antennas but the antenna on FR4 was scattered and did not radiate and focus directly to the desired targeted destination. Hence, the usage of metamaterial base is able to recover this weakness by focusing the radiation pattern to the desired coordinate.

Figure 8: Gain of the antenna on FR-4

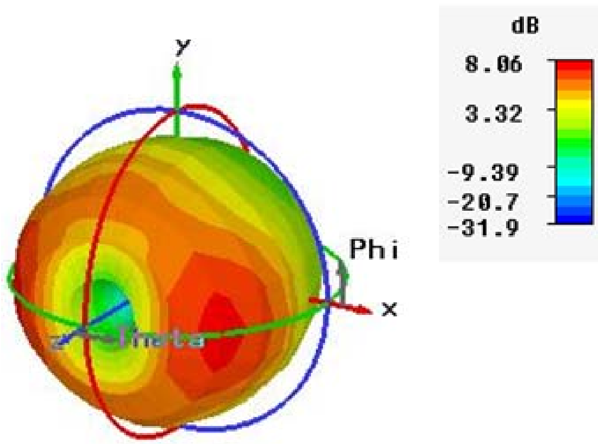
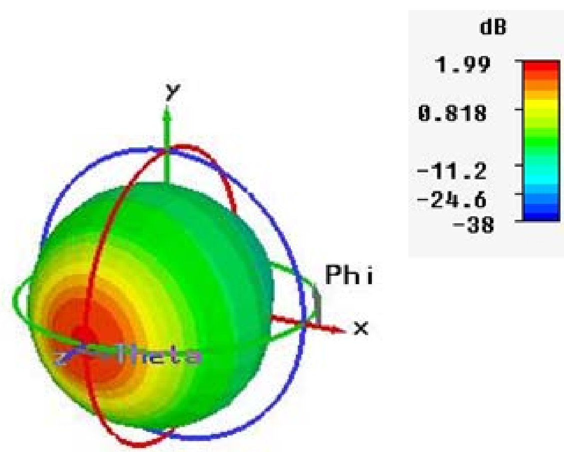


Figure 9: Gain of the antenna on metamaterial



4. Conclusion

This investigation shows that the split ring structure able to produce a metamaterial substrate. It has been successfully proven by the negative permittivity in the range of 4.6GHz to 4.9GHz. Applying the metamaterial in designing patch antenna is able to reduce size of the circuit area more than 50% of the overall dimensions. It is also able to improve the return loss from -22 dB to -24 dB as well as 1.5 dBi directivity gain higher than the antenna on FR-4.

5. Future Development

Several improvements to enhance the gain of the metamaterial antenna can be taken into consideration for future research. The metamaterial can be designed using different substrate and structure. Different type of patches and feeding techniques also may affect the performance of the antennas. Despite of using single unit cell, a combination of a number of unit cells can be applied in designing the antenna on metamaterial substrate.

6. Acknowledgement

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