An Enhancement of Bandwidth in Patch Antenna Using Metamaterial

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Abstract - **This project proposed a new generation of antenna that applies metamaterial as based construction of the antenna. Current bulky size antenna can easily be replaced by invented metamaterial antenna. The simulations of the metamaterial antenna as substrate have positive results with respect to the bandwidth and size of the antenna, while metamaterial antenna as cover also have positive results with respect to the bandwidth and directivity of the antenna. The omega structure was made of combination of two materials; Flame Retardant 4 and Perfect Electric Conductor which this design's resulting the formation of metamaterial. An investigation of the S-parameters has been carried out in determining the negative permittivity of this newly produced metamaterial. The return loss from the simulated metamaterial antenna as substrate is almost similar to the conventional antenna. Directivity of the conventional antenna was improved significantly with the use of metamaterial slab as cover of the antenna. The antennas lead to enhancing the technology to ease the customers by giving a smaller, cheaper and better performance of device.**

Keywords— antenna, metamaterial, permittivity

I. INTRODUCTION

The IEEE standard define antenna as part of a transmitting or receiving system which is designed to radiate or to receive electromagnetic waves [1]. In other words, the antenna is a transitional structure between free space and guiding device. Microstrip antennas have many unique and attractive properties like low in profile, light in weight, compact and conformable in structure, and easy to fabricate and to be integrated with solid-state devices [2]. Microstrip antennas have found wide applications in radio frequency design with single-ended signal operation. Recently, it can be seen used in radio frequency design with combination of metamaterial whether as cover or substrate.

Metamaterials are structured composite materials with unique electromagnetic properties due to the interaction of electromagnetic waves with the finer scale periodicity of conventional materials [3]. The person who is responsible in discovering the concept of metamaterials is Veselago in 1967 [4]. Veselago assumed the unknown materials has negative permeability and permittivity in the same frequency range and it show abnormal electromagnetic properties when he studied the uniform plane-wave propagation [4-6]. Negative permittivity means the material produce may not be easily available in nature, physically unique and has unusual realizable response function. As a result, Veselago referred the material left-handed material (LHM) which has reverse basic feature of light, such as negative refractive index (NRI) [5, 6]. Surprisingly, Veselago got only little attention for his work until came to year 2000 when Smith further studied the LHM and realized this material is a periodically-arranged conducting concrete and also shows extraordinary properties [5].

The first structure that was used to prove the existing of metamaterial was split ring structure invented in 2001 by Shelby Smith and Schultz at the University of California [7]. Three new structures were proposed in year 2005, starting with symmetrical ring structure than omega structure and the latest one was S structure [8]. In this paper, omega structure was used to build the metamaterial antenna because of its perfectly conducting shape and can produce better performance from the other shape [8]. The proposed design was simulated and analyzed using Computer Simulation Technology (CST) Microwave Studio.

II. METAMATERIAL

The first step of the construction is to choose reliable and potential structure that can become metamaterial. Some of the famous structures are rod structure, split-ring structure, symmetrical-ring structure, S-structure and omega structure [9]. This paper will take omega structure as it basic structure to realize the existing of metamaterial. The dimension of the omega structure is shown in Fig. 1.

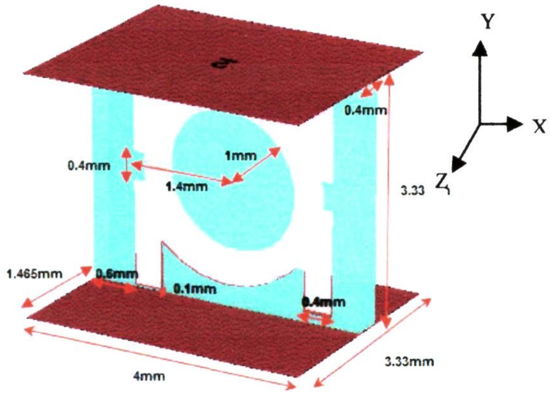

Figure 1: A unit cell of omega structure in a waveguide

The omega structure consists of two parts which are the substrate and the omega structure itself. In this paper, the substrate used was Flame Retardant 4 (FR-4) and the omega structure built by Perfect Electric Conductor (PEC). PEC usage is important in assuming the ideal case during simulation in obtaining best results from the metamaterial response. The details of FR-4 is as shown in Table I.

Table I
FR-4 SUBSTRATE PROPERTIES

Properties	Values
Permittivity, ε	4.9
Loss Tangent	0.025
Permeability, μ	1
Substrate Height, h	0.4mm

Permeability was set to one because the substrate used was a dielectric material which has no metal or magnetic properties. In other word, it is for ideal case assumption.

This omega structure was constructed and simulated using CST Microwave Studio. Referring to figure 1, waveguide ports were set at bottom and below on Y-axis where the signal or the wave penetrates into the metamaterial. PEC boundary conditions were implemented at front and back on Z-axis and perfect magnetic conductor (PMC) boundary conditions were placed at left and right on X-axis [9].

PBA mesh type was chosen and mesh density was fixed to 10 lines per wavelength with refinement at PEC edges by factor of 4 [9]. Transient solver was used to simulate the metamaterial construction in the CST Microwave Studio and S-data retrieved for analysis to determine the permittivity of metamaterial.

There are four popular methods of conversion from S-data to dielectric properties that usually used in radio frequency analyses. The four techniques are Nicolson-Ross-Weir (NRW) technique, NIST iterative technique, new non-iterative technique and short circuit line technique [10].

The method that has been chosen to prove this metamaterial is NRW technique which provides simple and direct calculation of both permeability and permittivity from the S-data [10]. Furthermore, it is the most frequently used technique for performing such conversion [10].

NRW method will use S-data such as S_{11} and S_{21} that obtained from the CST Microwave Studio to calculate the reflection coefficient (Γ).

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

where

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

The magnitude of the reflection coefficient (|Γ|) must be less than one in order to get the correct root (*X*) which in form of s-parameter. Next step is to calculate the transmission coefficient (T) of the metamaterial.

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

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

where

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

where

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

Number of roots, *n* can be determined by applying equation (6), followed by equation (7) and lastly, the value from equation (7) is substituted into equation (5). The obtained value of *n* must be rounded up to the nearest integer in obtaining the actual number of roots.

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

where

Λ = complex wavelength
ε_r = complex initial guess of material permittivity
μ_r = complex initial guess of material permeability
λ_o = wavelength in free space
λ_c = cut-off wavelength

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

Equation (8) is obtained by substituting value in equation (4) into it.

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

The permeability (μ_r) of the metamaterial was obtained by replacing value from equation (1) and equation (6) into equation (9).

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

The permittivity (ε_r) of the metamaterial was obtained by replacing value from equation (8) and equation (9) into equation (10).

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

All formulae used to obtain the permittivity of the metamaterial were programmed in MATLAB R2007b to obtain a plot of permittivity value of metamaterial versus frequency.

III. THE PATCH ANTENNA

The rectangular microstrip patch antenna system consists of several parts such as feeder line, patch, ground and substrate. The dimension of the antenna as shown below:

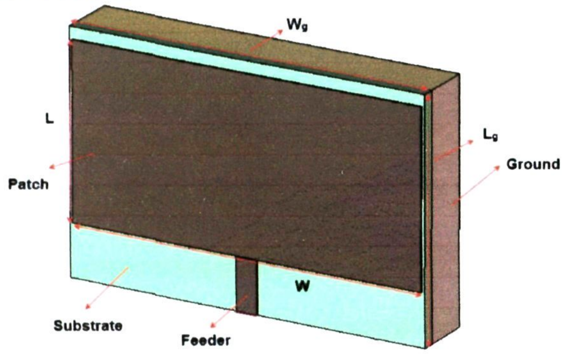

Figure 2: A view of a conventional antenna

Patch, feeder line and ground are PEC based structure while the substrate is FR-4. In this paper, the antenna will be designed to operate at 11.5GHz. The dimensions of the antenna were achieved by applying some basic formulae of an antenna design [11]. Firstly, it is important to get the width and length of the patch antenna before the width and length of the substrate can be achieved.

Patch Width

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{11}$$

where

c = speed of light ($3x10^8$ m/s)
f_o = operating frequency in GHz
ε_r = permittivity of material

Effective Dielectric Constant

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{\frac{1}{2}} \tag{12}$$

where

h = substrate thickness (0.4mm; as stated in Table I)

Effective Length

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \tag{13}$$

Length Extension

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

Patch Length

$$L = L_{eff} - 2(\Delta L) \tag{15}$$

Patch width value from equation (11) and patch length from equation (15) were substituted in equation (16) and equation (17) respectively to get the corresponding substrate width and substrate length.

Substrate Width

$$W_g = 6h + W \tag{16}$$

Substrate Length

$$L_g = 6h + L \tag{17}$$

Formulae above were used to calculate the initial value of the antenna dimensions with respect to 11.5GHz operating frequency and also FR-4 permittivity as well as it thickness. The calculated result was tabulated is shown in table II.

Table II
CONVENTIONAL ANTENNA DIMENSIONS

Patch Width, *W*	7.594mm
Patch Length, *L*	5.237mm
Substrate Width, W_g	9.994mm
Substrate Length, L_g	7.637mm

Feeder line width and length were acquired using Line Calc. Using the FR-4 details and the operating frequency as the input for the Line Calc, the feeder line width is 0.673mm while transmission line length is 1.683mm.

All of these details were exported into CST Microwave Studio to be design and simulate using transient solver. Optimization process was done along the way to get the suitable result for its performance in term of return loss and bandwidth.

IV. APPLICATION OF METAMATERIAL

Usually there are two methods on how metamaterial can be applied to antenna. The two methods are metamaterial as substrate of the antenna or metamaterial as a cover of a conventional antenna.

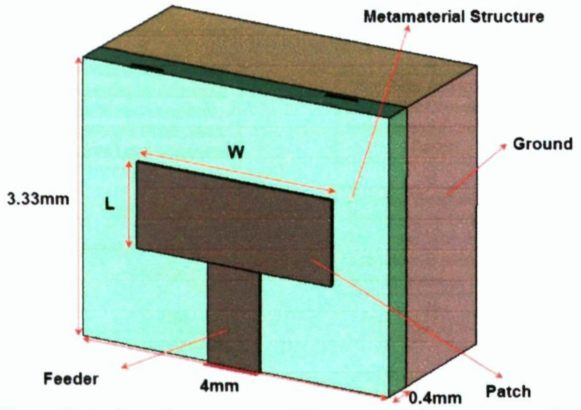

Figure 3: A view of a metamaterial antenna using metamaterial as a substrate

a) Metamaterial as Substrate

In construction of metamaterial antenna with metamaterial as a substrate, the only difference from construction of conventional antenna is the FR-4 substrate was replaced with the metamaterial. The antenna substrate mostly will follow the metamaterial dimension, so the patch and feeder line of this antenna will decrease gradually from the conventional antenna. The dimension of the antenna is shown in Fig. 3.

The feeder line width was kept constant in order to maintain the impedance of the feeder line itself. This metamaterial antenna will be evaluated at 11.5GHz, same as the conventional antenna to compare the performance of both antennas. CST Microwave Studio transient solver has used to simulate this metamaterial antenna. Patch width, patch length and feeder line length were continuously varied until a better result was obtained by comparing with the conventional antenna.

b) Metamaterial as Cover

In the construction of metamaterial antenna with metamaterial as a cover, six unit cell of metamaterial omega structure was combined in producing a slab of omega structure. The slab figure is shown in figure below:

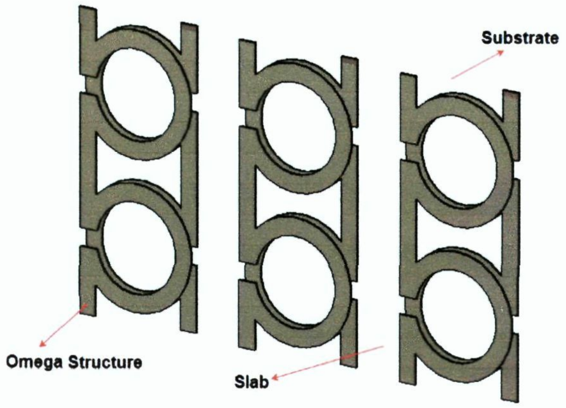

Figure 4: A slab of omega structure

The slab was put at some distance from the conventional antenna to make it work as a cover for the antenna. The combination between both slab and conventional antenna is shown in Fig. 5.

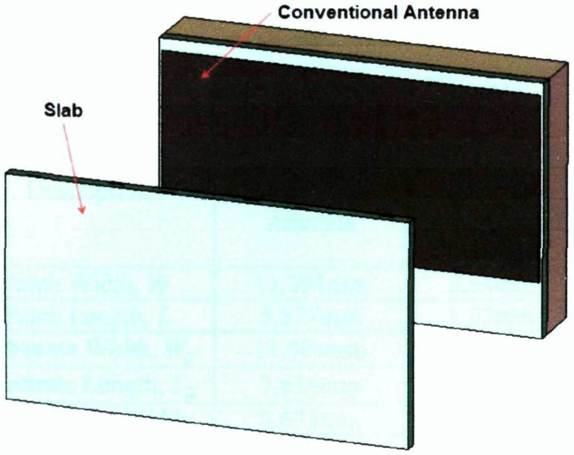

Figure 5: A view of a metamaterial antenna using metamaterial as a cover

This antenna was evaluated at 11.5GHz. Transient solver mode in CST Microwave Studio was used to simulate this metamaterial antenna. The distance between slab and conventional antenna was changed frequently to get best return loss and bandwidth.

All design process to produce both metamaterial antennas, whether as substrate or as cover was summarized in the flowchart Fig. 6.

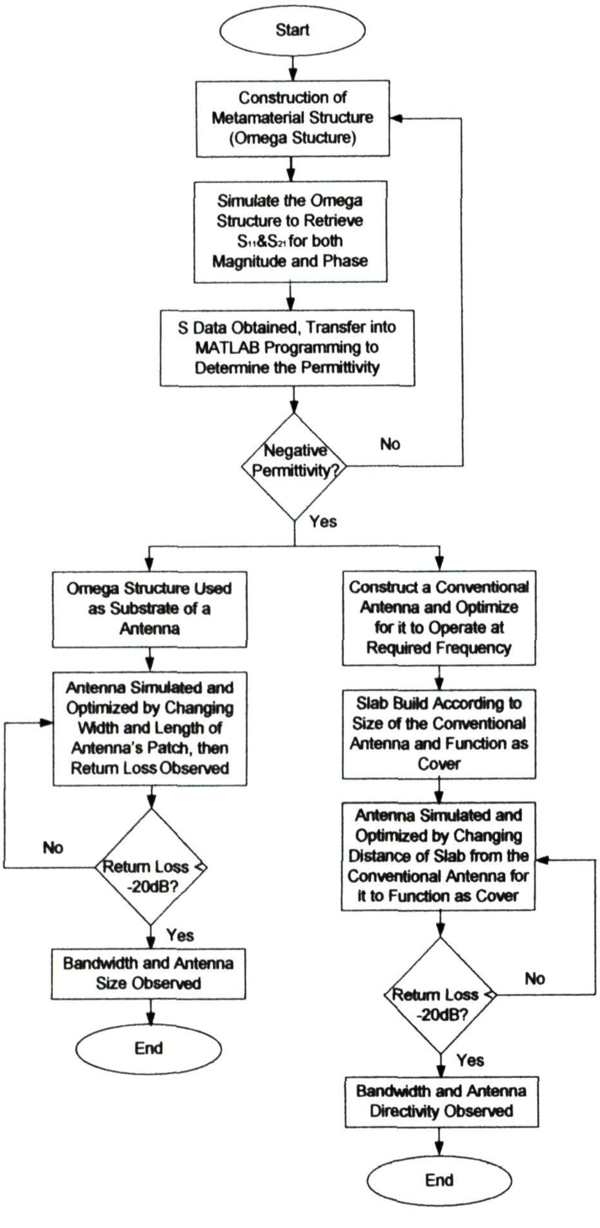

Figure 6: Flow chart for construction of metamaterial antenna as substrate and cover

V. RESULTS AND DISCUSSION

Fig. 7 shows the plot that appears from process of retrieving permittivity from S-data. Response on the graph indicates that the metamaterial has negative permittivity starting from 10.5 GHz until 20 GHz. Negative value of permittivity also can be observed at the operating frequency of the metamaterial antenna that is 11.5GHz with permittivity value of -5.18. This negative permittivity validates the metamaterial structure.

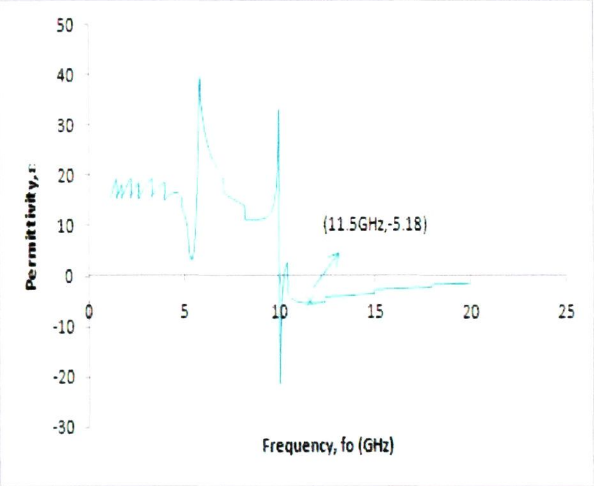

Figure 7: Permittivity as a function of frequency

After optimization process for both conventional and substrate metamaterial antenna, new dimensions for both antennas were obtained. These antennas can produce positive result for their return loss and bandwidth, but the most interesting part is the metamaterial antenna produced is approximately three times smaller than conventional antenna that also operates at frequency of 11.5GHz. Comparisons for both antennas are shown in Table III.

Table III

COMPARISON BETWEEN CONVENTIONAL ANTENNA AND SUBSTRATE METAMATERIAL ANTENNA

Description	Conventional Antenna	Substrate Metamaterial Antenna
Patch Width, W	11.394mm	2.54mm
Patch Length, L	5.577mm	1.03mm
Substrate Width, W_g	11.594mm	4mm
Substrate Length, L_g	7.636mm	3.33mm
Feeder Line Width	0.673mm	0.673mm
Feeder Line Length	1.683mm	1.2mm

Clearly it can be seen from Tab. III, metamaterial structure were proven to reduce the size of the antenna if and only if the magnitude for the negative permittivity is in small range of value. In this paper, the metamaterial permittivity is -5.18 at the operating frequency, which can be consider small in magnitude for negative number.

The antenna can be realized in small size by using metamaterial structure due to the abnormality of its electromagnetic properties which can lead to opposite characteristic such as smaller frequency can lead to smaller wavelength and thus smaller size obtain as what has been proved with metamaterial antenna specification above.

Fig. 8 shows the plot of return loss for conventional antenna, substrate metamaterial antenna and cover metamaterial antenna. The return loss for those antennas are less than -20dB which can be considered as good antenna because it is important that very small amount of reflection wave return back to the antenna as the reflection power can damage the microstrip patch antenna. Small value of return loss will ensure the operating antenna at its maximum power.

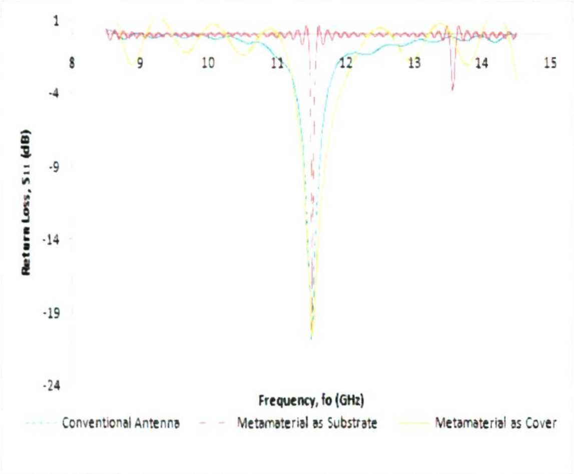

Figure 8: Return loss as a function of frequency

Bandwidth of conventional antenna (BW1) is much bigger than bandwidth of substrate metamaterial antenna (BW2) but smaller than cover metamaterial antenna as in Fig. 9. The bandwidth for conventional antenna is 0.2GHz. For substrate metamaterial antenna is 0.03GHz while cover metamaterial antenna is 0.3GHz. Bandwidth for these antennas cannot be categorized as broad bandwidth because the antenna design techniques that have been implemented are only suitable for narrow band design.

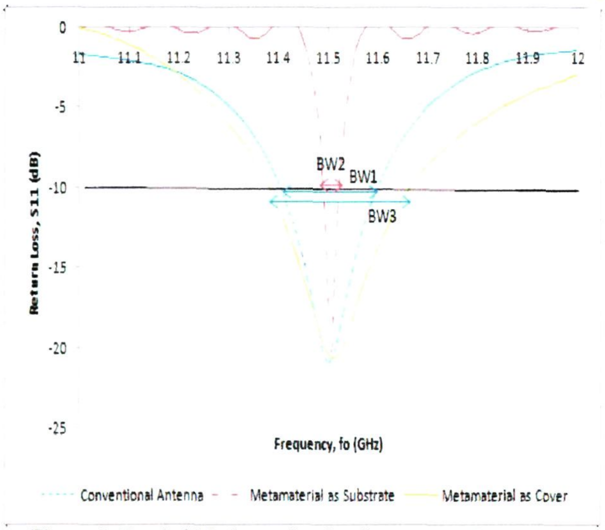

Figure 9: Bandwidth determination from return loss graph

Despite having smaller bandwidth for substrate metamaterial antenna it is still able to operate at antenna operating frequency, 11.5GHz which within the bandwidth range. This shows that the substrate metamaterial antenna is reliable to operate normally at desired frequency. The reduction of bandwidth can be avoided by using cover metamaterial antenna. It is proven that the antenna has an increase in bandwidth of 0.1GHz with the size remain same as conventional antenna.

With an addition of slab to conventional antenna, the directivity of cover metamaterial was improved. The conventional antenna has directivity of 6.2646 dBi while cover metamaterial antenna has directivity scale to 7.133 dBi.

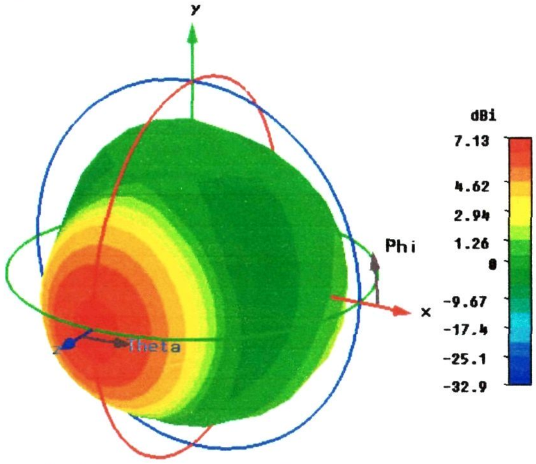

Figure 10: Directivity radiation of cover metamaterial antenna

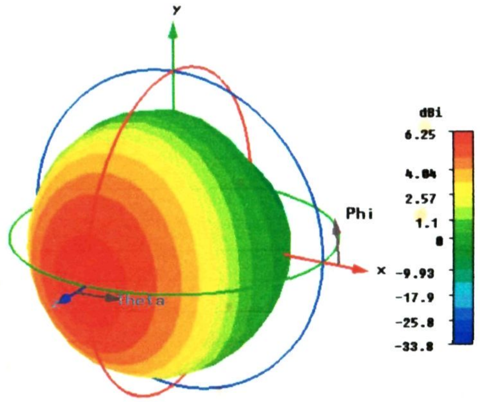

Figure 11: Directivity radiation of conventional antenna

Fig. 10 and 11 show directivity of both cover metamaterial and conventional antenna respectively. High directivity of an antenna shows that antenna have high intensity to radiates. The beam focus of the antenna become more accurate and thus increases the performance in signal transmission.

VI. CONCLUSION

The tested omega structure has been proved to be a metamaterial as the desired frequency showed a negative permittivity. A step-by-step procedure in designing metamaterial antenna was presented in this paper. A rectangular microstrip patch antenna which is smaller than the conventional antenna was successfully implemented using this method. A conventional antenna with an improved directivity was successfully designed by utilizing the usage of metamaterial slab. A good return loss for the substrate and the cover of metamaterial antennas were obtained. An improved bandwidth and directivity for the cover of metamaterial antenna proved that metamaterial can enhance overall performance of an antenna.

VII. FUTURE DEVELOPMENT

It is recommended that several improvements in terms of enhancing the bandwidth of the antenna will be taken into consideration for future research. The bandwidth of the antenna that can operate in metameterial region can be further enhanced. The bandwidth of the antenna will proportionally broad according to the material that can operate at broadband for wider range of negative permittivity. The future metamaterial antenna can be designed on different substrate with different properties and structures. The third recommendation is to design using different type of patches and feeding techniques.

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