Upgrading Bandwidth Of Rectangular Patch Antenna Using Metamaterial

Ahmad Syazwan Bin Nasaruddin
Faculty of Electrical Engineering, Universiti Teknologi MARA,
40450 Shah Alam, Selangor, Malaysia

Abstract— **This paper is proposed a metamaterial in constructing a patch antenna. It is done by implementing a metamaterial as substrate of the antenna. The study is concentrating on X-band frequency at 11.28 GHz. This design can reduce the size of the antenna as well as maintaining the return loss response and able to increase the bandwidth. The newly invented metamaterial antenna maintained return loss of less than -20dB and 300MHz wider bandwidth if compared to the conventional antenna. The size of the metamaterial antenna is reduced by a factor of 2. The metamaterial is obtained by combining two materials which are the Flame Retardant 4 (FR-4) and the Copper in the structure of Symmetrical-Ring. The S-parameter obtained from simulation of the metamaterial is ensured to be negative in order for it to be a metamaterial. This metamaterial antenna is surely good news for communication industries as antenna can now be produced at smaller size but still can response similarly or even better than the conventional antenna nowadays. This metamaterial antenna has positive future in helping the telecommunication industries to move one step further in enhancing their technology thus giving satisfaction to the customers.**

Keywords— patch antenna, metamaterial

I. INTRODUCTION

The IEEE standard definition of terms for antenna defines the 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 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]. Conventional antenna often limits the application of the antenna since they are governed by the 'right hand rule' which determine how electromagnetic wave should behave. Metamaterial offers an alternative solution to widen the antenna applications using the 'left hand rule'[3]. Metamaterials are structured composite materials with unique electromagnetic properties due to the interaction of electromagnetic waves with the finer scale periodicity of conventional materials [4]. Microstrip antennas have found wide applications in radio frequency design with single-ended signal operating space and guiding device. Microstrip antennas have manon. Recently, microstrip antennas can be seen for use in radio frequency design with combination of metamaterial as a substrate.

The person who is responsible in discovering the concept of metamaterials is Veselago in 1967 [4]. He assume 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], [5], [6]. As a result, he referred the material left-handed material (LHM) which has reverse basic feature of light, such as negative refracstive index (NRI) [5], [6]. Surprisingly, he 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 [6]. Therefore, this paper is concerning to enhance the performance of the antenna and realize it to smaller size.

The first structure that used to prove the existing of metamaterial was split ring structure that invented on year 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, Symmetrical Ring structure is used to build the metamaterial antenna because of it perfectly conducting shape and can produce better performance from the other shape [8]. The simulation of proposed Symmetrical Ring structure is done by using Computer Simulation Technology (CST) Microwave Studio to analyze the Symmetrical Ring metamaterial structure when it is combined with the conventional antenna as the substrate with respect to their S parameter responses.

This paper will focus on the construction of rectangular patch antenna using metamaterial as substrate. The properties of metamaterial structure and radiation characteristics of the rectangular patch antenna are also investigated.

II. METHODOLOGY

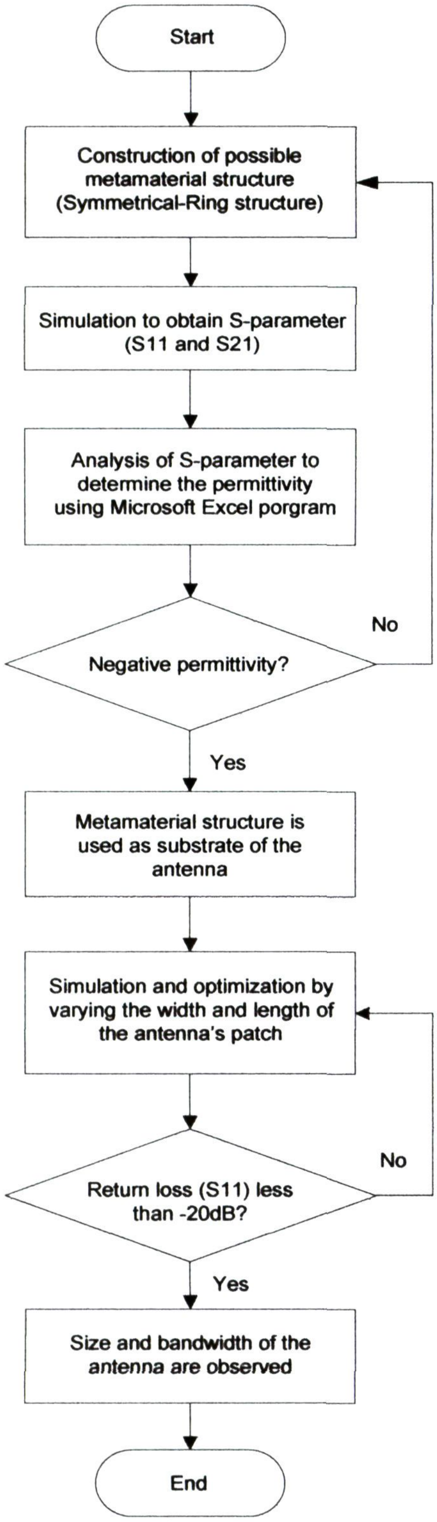

Figure 1 : Flow chart of overall process in metamaterial antenna construction

To start off with the construction of metamaterial, it is crucial to choose a reliable and potential structure that can act as a metamaterial. There are several structures such as Omega structure, S structure, Split-Ring structure, Rod structure and Symmetrical-Ring structure [9]. This paper will propose the Symmetrical-Ring structure as its basic structure in realizing the existing of the metamaterial. The Symmetrical-Ring structure has dimensions as shown below :

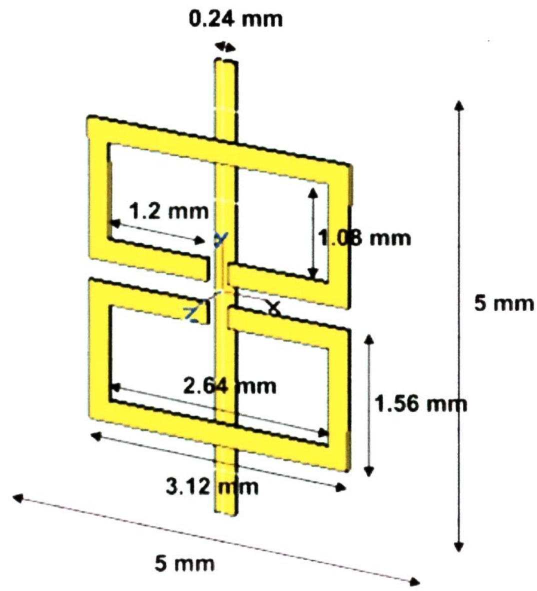

Figure 2 : A unit cell of the Symmetrical-Ring structure in a waveguide

The Symmetrical-Ring structure consists of three parts which are a substrate, a symmetrical-ring structure itself and a wire strip. Flame Retardant 4 (FR-4) is used as the substrate. As for the symmetrical-ring structure and the wire strip, they are constructed using Copper. Details regarding FR-4 are shown below :

TABLE I
FR-4 SUBSTRATE PROPERTIES

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

The permeability is set to 1 due to the dielectric material of the substrate which has no metal or magnetic properties. In other words, an ideal case assumption for those properties.

Construction of the Symmetrical-Ring structure is done by using Computer Simulation Technology (CST) Microwave Studio. The same application is also used for the simulations. Waveguide ports are set at both top and bottom of the Y-axis in which the signal or wave penetrates into the metamaterial. Perfect Electric Conductor (PEC) boundary conditions are set at both front and back of the Z-axis while Perfect Magnetic Conductor (PMC) boundary conditions are set at both left and right of the X-axis [9].

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

In radio frequency analyses, the dielectric properties can be obtained by analyzing the S-data. There are several methods to convert the S-data into dielectric properties. Those methods are NIST iterative, new non-iterative, short circuit line and Nicolson-Ross-Weir (NRW) [10].

In this paper, NRW method is chosen in analyzing the S-data. This is due to its simple and direct calculation of both the permeability and permittivity from the S-data [10]. It is also the most famous and most commonly used technique for performing such conversion [10].

S_{11} and S_{21} of the S-data which are obtained from the simulation using the CST Microwave Studio are used to calculate the reflection coefficient.

Reflection coefficient is given by :

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

where

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

In order to find the correct root, the magnitude of the reflection coefficient ($|\Gamma|$) must be less than one and in the form of S-parameter. Next step is to calculate the transmission coefficient of the metamaterial.

Transmission coefficient is given by :

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

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

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 (radian)

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

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

where

Λ = complex wavelength
ε_r = initial guess of material permittivity
μ_r = 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) been obtained by substituting value in equation (4) into it.

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

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

Permeability is given by :

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

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

Permittivity is given by :

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

In order to obtain the value of the permittivity, a program is constructed by using Microsoft Excel. All calculation is done automatically instead of doing it manually. A plot of permittivity against frequency is shown.

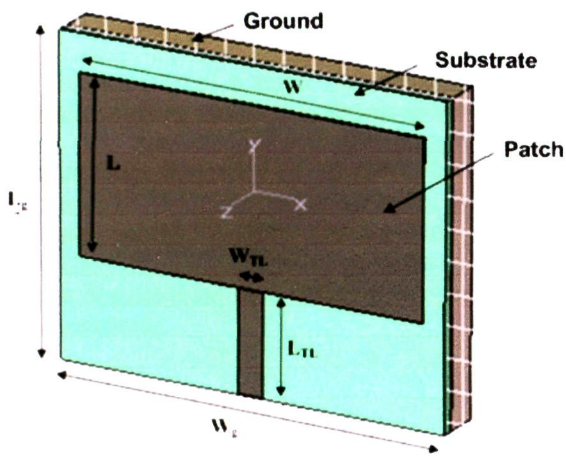

Figure 3 : A view of the conventional antenna

The rectangular microstrip patch antenna system consists of several parts such feeder line, patch, ground and substrate. The dimensions of the antenna are as shown as in Figure 3.

FR-4 is once again set as the substrate while PEC is chosen for the patch, transmission line and ground. In this paper, the antenna is designed to operate at frequency of 11.28 GHz. The dimensions of the antenna are obtained from the basic antenna formula for antenna design [11].

The calculation is started off with the dimensions of the width and length of the patch antenna.

Patch width is given by :

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

where

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

Effective dielectric constant is given by :

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

where

$h =$ substrate thickness

Effective length is given by :

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

Length extension is given by :

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

Patch length is given by :

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

Once the dimensions of the width and length of the patch antenna are obtained, the dimensions of the width and length of the substrate can now be calculated. Value of the patch width and length are substitute into equation below respectively in order to get the corresponding substrate width and substrate length.

Substrate width is given by :

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

Substrate length is given by :

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

All the values obtained using the formulas are the initial value of the dimensions of the antenna in order for it to operate at 11.28 GHz. Also, FR-4 permittivity and thickness is used. The result is tabulated in table below.

TABLE II
CONVENTIONAL ANTENNA DIMENSIONS

Patch width, W	7.94mm
Patch length, L	5.50mm
Substrate width, W_g	10.34mm
Substrate length, L_g	7.90mm
Transmission Line Width, W_{TL}	0.84mm
Transmission Line Length, L_{TL}	3.58mm

As for the transmission line, the width and length are obtained from Line Calc. The inputs for the Line Calc are the FR-4 details and the operating frequency.

The construction and simulation of the conventional antenna are done using CST Microwave Studio. Optimization is also done to get suitable result in term of performance focusing on return loss and bandwidth .

III. RESULTS AND DISCUSSION

The response of a single unit metamaterial of a Symmetrical-Ring structure is shown as below where it can be seen clearly that the permittivity are negative from frequency of 10.424 GHz to 11.344 GHz and 12.264 GHz to 14 GHz. In this paper, frequency of 11.28 GHz will be used with the permittivity of -1.67. Negative permittivity indicates that the Symmetrical-Ring structure has been proven as metamaterial.

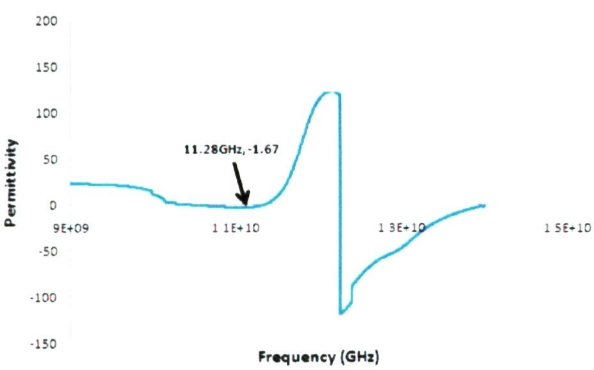

Figure 4 : Permittivity as a function of frequency

The metamaterial is then used as the substrate for the construction of the antenna. Two sets of antenna are constructed, the conventional antenna as in Figure 3 and the metamaterial antenna as in Figure 5.

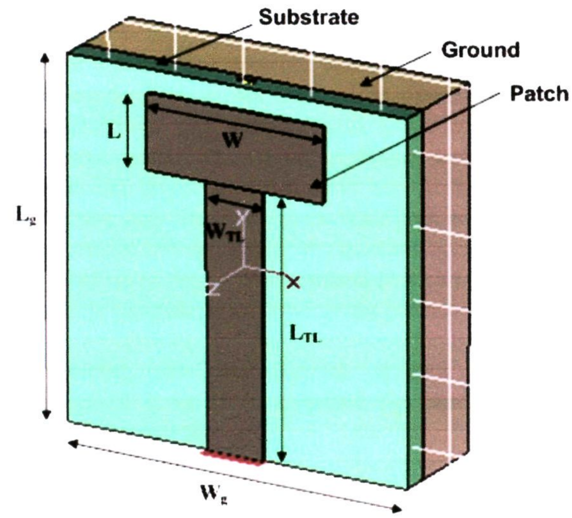

Figure 5 : Metamaterial antenna

Optimization is done to achieve the desired response from both antennas. First, it can be seen that metamaterial antenna has smaller size compared to the conventional antenna. The comparison of sizes are shown in table below :

TABLE III
COMPARISON BETWEEN CONVENTIONAL ANTENNA AND METAMATERIAL ANTENNA

Description	Conventional Antenna	Metamaterial Antenna
Patch Width, W	11.60mm	2.60mm
Patch Length, L	5.75mm	1.05mm
Substrate Width, W_g	13.00mm	5.00mm
Substrate Length, L_g	10.31mm	5.00mm
Transmission Line Width, W_{TL}	0.84mm	0.84mm
Transmission Line Length, L_{TL}	3.33mm	3.65mm

From the table, the size of the antenna can be said to reduce by at least half of its size. The antenna can be reduced to such small size is due to the abnormality of the metamaterial structure electromagnetic properties which can lead to opposite characteristic such as smaller frequency can lead to smaller wavelength thus smaller size.

Figure shows the plot of return loss for both conventional and metamaterial antenna. Both antennas indicate good performance where the return loss are less than -20dB. It is important to have a very small value of return loss as it indicates only small amount of reflection wave that return back to the antenna. The reflection power can damage the antenna [11]. Small value of return loss will lead the antenna to operate closely at its maximum power.

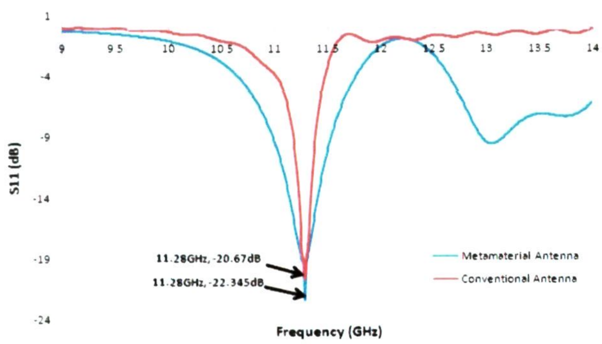

Figure 6 : Return loss for both conventional and metamaterial antenna

As for bandwidth, it can be seen that metamaterial antenna has slightly wider bandwidth compared to the conventional antenna.

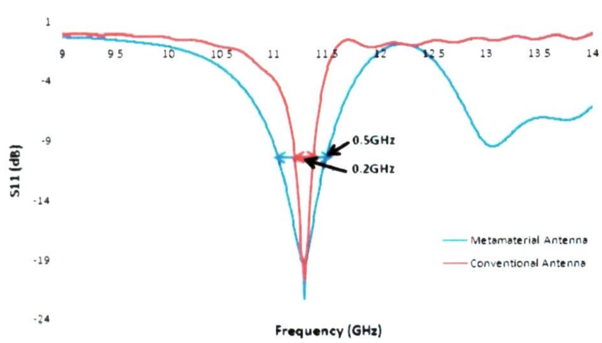

Figure 7 : Bandwidth for both conventional and metamaterial antenna

The conventional antenna has only 0.2GHz of bandwidth while for the metamaterial antenna, it has 0.5GHz bandwidth.

IV. CONCLUSION

It can be seen throughout this paper that metamaterial has successfully proven by having negative permittivity at certain range of frequencies. The negativity is due to the unique structure and its dimension.

Implementing metamaterial as the substrate of the antenna, the size has been reduced by a factor of 2. The return loss is still maintained less than -20dB. The bandwidth of the metamaterial antenna is 300MHz wider compared to the conventional antenna.

V. FUTURE DEVELOPMENT

For future development, several factors must be considered. First is the method in determining the permittivity of the metamaterial substrate from S-parameter. Although several methods already exist such as the NIST iterative, new non-iterative, short circuit line and Nicolson-Ross-Weir (NRW), it is still not accurate due to the approximation aprroaches. It is important to find a new method that can contribute to a more accurate to determine the permittivity.

Second, the metamaterial antenna could be investigated in order to enhance the bandwidth for broadband antenna.

Third, the combination of metamaterial and structure can also be varied to produce a better metamaterial.

ACKNOWLEDGEMENT

The author would like to thank Mohd Huzaimy Jusoh and Ahmad Asaari Sulaiman for their supervisions, guidance and support in completing this project. Also, thanks to Shareen Adlina Shamsudin for her opinions, ideas and knowledge in constructing the metamaterial, antenna and also in using the CST Microwave Studio software..

REFERENCESS

[1] "IEEE standard definitions of terms for antennas," *IEEE Std 145-1983,* 1983.

[2] Y. P. Zhang and J. J. Wang, "Theory and analysis of differentially- driven microstrip antennas," *Antennas and Propagation, IEEE Transactions* , vol. 54, pp. 1092-1099, 2006.

[3] A. Semichaevsky and A. Akyurtlu, "Homogenization of metamaterial-loaded substrates and superstrates for antennas," *Progress In Electromagnetics Research,* vol. 71, pp. 129-147, 2007.

[4] M. Lapine and S. Tretyakov, "Contemporary notes on metamaterials," *Microwaves, Antennas & Propagation, IET,* vol. 1, pp. 3-11, 2007.

[5] E. Nader and R. W. Ziolkowski, "A positive future for doublenegative metamaterials," *Microwave Theory and Techniques, IEEE Transactions,* vol. 53, pp. 1535-1556, 2005.

[6] L. Le-wei, Y. Hai-ying, W. Qun, and C. Zhi-ning, "Broad-bandwidth and low-loss metamaterials: theory, design and realization," *Journal of Zhejiang University SCIENCE A,* vol. 7, pp. 5-23, 2006.

[7] B. Szentpali, "Metamaterials: a new concept in the microwave technique," in *Telecommunications in Modern Satellite, Cable and Broadcasting Service, 2003. TELSIKS 2003. 6th International Conference*, pp. 127-132 vol.1, 2003

[8] L. Ran, J. Huangfu, H. Chen, X. Zhang, K. Cheng, T. M.

Grzegorczyk, and J. A. Kong, "Experimental study on several left-handed metamaterials," *Progress In Electromagnetics Research*, vol. 51, pp. 249–279, 2005.
[9] B.-I. Wu, W. Wang, J. Pacheco, X. Chen, T. Grzegorczyk, and J. A. Kong, "A study of using metamaterials as antenna substrate to enhance gain," *Progress In Electromagnetics Research*, vol. 51, pp. 295-328, 2005.
[10] Rhode&Schwarz, "*Measurement of dielectric material properties*," 2006.
[11] Z. Awang, *Microwave Engineering for Wireless Communications: Prentice Hall, 2006.*