Design of Interdigital Bandpass Filter on Metamaterial Substrate

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Abstract—**In this paper, a new invention of multilayer bandpass filter that consist of metamaterial as the substrate. This presence of metamaterial as a new composite and artificial dielectric give good results in terms of the return and insertion losses as well as stopband attenuation. An S-structure with combinations of Flame Retardant 4 (FR-4) and Perfect Electric Conductor (PEC) has successfully performed metamaterial. The metamaterial behaviors are only viable at certain frequency and for certain design. A lot of effort has been done to prove that the design structure follows the metamaterial behavior. Based on simulated result, the return loss of metamaterial bandpass filter is two times better performance than conventional bandpass filter. At center frequency, the insertion loss and stopband attenuation for metamaterial bandpass filter have been improved about 58.6% and 14.2% respectively as compared to the conventional bandpass filter.**

Keywords—Bandpass filter, metamaterial, microstrip, interdigital bandpass filter, Ku-band

I. Introduction

The rapid growth of mobile wireless communication systems has led to a great increasing demand for miniaturized and compact microwave filters since mobile platforms have a limited space for required filters. Over the last decade, planar microstrip filters with various configurations have been proposed [1]-[2]. Microstrip filters are filters constructed with coupled microstrip resonators. In a microstrip filter, microstrip resonators are arranged on the surface of a dielectric substrate, the substrate having a conductive ground plane beneath it [3].

As a widely used type of microwave filter, the interdigital bandpass filter is well known for its attractive features like wideband, low loss and compact structure [4]-[7]. The compactness of interdigital filter makes it a very popular filter where bandpass is concern In this paper, a compact cross-coupled interdigital bandpass filter is designed by using multilayered structure.

The development of artificially structured electromagnetic materials termed as metamaterial, has led to the realization of phenomena that cannot be obtained with natural material. The word metamaterial literally refers to any substance possessing characteristics beyond behavior of normal materials. Materials with negative permittivity and permeability in certain frequency range or known as left-handed material (LHM) are the example of metamaterial that molded into minds. Negative permittivity means the material produce was new, may not be easily available in nature, physically unique and has unusual realizable response function. A metamaterial is a material which gains its properties from its structure rather than from its composition [8].

In this paper, a four pole interdigital bandpass filter is presented. The designed filter is 0.01 dB Chebyshev ripple, and 31% fractional bandwidth, w that operates at center frequency of 13.06 GHz which is lies in Ku-band (12 GHz-18 GHz) frequency range with low cut-off frequency of 12.76 GHz and high cut-off frequency of 13.36 GHz. The minimum attenuation loss at 14.7 GHz and the bandwidth are at least -20 dB and 0.6 GHz respectively. The bandpass filter specifications are summarized in Table I.

TABLE I
BANDPASS FILTER DESIGN SPECIFICATIONS

Centre frequency, f_0	13.06 GHz
High cut-off frequency, f_H	13.36 GHz
Low cut-off frequency, f_L	12.76 GHz
Bandwidth	600 MHz
Stopband attenuation	At least -20 dB at 14.7 GHz

II. Methodology

A. *Metamaterial Design and Its Determination*

The first step is to determine the potential structure which can perform metamaterial behavior. There are some structures that are available to design a metamaterial such as Split-Ring Resonator (SRR) structure, Omega structure, S-structure, Rod structure, Symmetrical-Ring structure [9]. For this paper, the S-structure is chosen as a metamaterial design structure because it is easy to be constructed. The dimension for the structure is 4 mm × 5.4 mm × 0.5 mm as shown in Fig 1. The ports for both input and output are set at Y-axis so that the propagation will be along the Y-axis. The Flame Retardant 4 (FR-4) is used underlay the S-structure, while the S-structure is made up of Perfect Electric Conductor (PEC). PEC materials are exhibiting infinite conductivity and it is assume to be ideal.

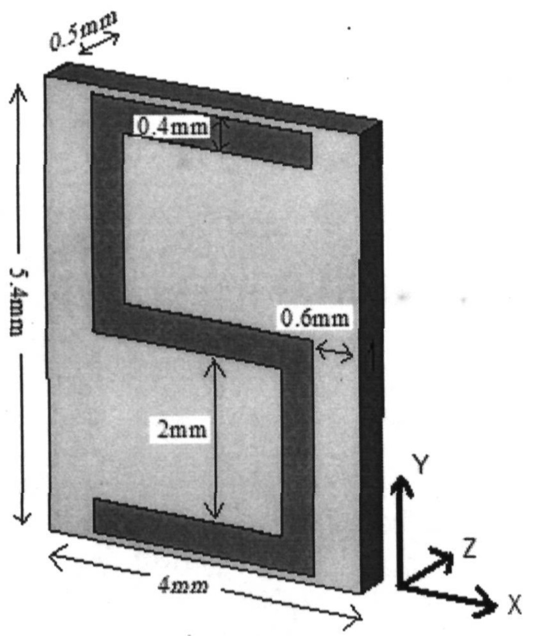

Fig. 1. 1 unit cell of S-structure

The detail properties of the substrate are listed on the Table II below.

TABLE II
FR-4 SUBSTRATE PROPERTIES

Permittivity, ε	4.9
Loss Tangent	0.025
Permeability, μ	1
Substrate Height, h	0.5mm

The CST Microwave Studio software is used to simulate and to obtain the S-parameters data. The boundary condition has been set as it has important consequences in the propagation of radiowave transmission [10]. Transient solver is used to simulate the metamaterial construction in the CST Microwave Studio software and S-parameter data were obtained for further analysis to determine the permittivity of metamaterial.

There are some methods or techniques used and that can be applied to determine the negative permittivity of metamaterial. The four common methods are Nicolson-Ross-Weir (NRW) technique, NIST iterative technique, new non-iterative technique and short circuit line technique [11]. In this paper, the Nicholson-Ross-Weir (NRW) method is applied to make verification for metamaterial based on S-parameter obtained before. This is because NRW method provides simplified and direct calculations of both permittivity and permeability from the S-parameter data. Furthermore, it is also the famous and most commonly used to determine the metamaterial behavior [11].

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

Reflection Coefficient

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

where

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

The magnitude of the reflection coefficient $(|\Gamma|)$ must be less than one in order to get the realizable root (X) which in form of S-parameter. The next step is to calculate the transmission coefficient, T of the metamaterial.

Transmission Coefficient

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

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

where

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

where

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

Equation (5), (6) and (7) are used to determine the number of roots, n. The obtained value of n must be rounded up to the nearest integer in order 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 of wavelength
ε_r = initial guess of material permittivity
μ_r = initial guess of material permeability
λ_0 = wavelength in free space
λ_c = cut-off wavelength

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

Then, by substituting the value from (4), the (8) can be obtained.

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

The permeability, μ_r of the metamaterial has been obtained by replacing the value from (1) and (6) into (9). Then, the permeability is given by:

Permeability

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

Next, the value from (8) and (9) are substituted into (10) to determine the permittivity, ε_r of the metamaterial.

Permittivity

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

All the formulae above are programmed in MATLAB R2007b and a graph of permittivity versus frequency is the output. This graph is used to determine the negative permittivity at the design frequency.

B. *Conventional Bandpass Filter Design*

After the suitable structure for metamaterial is chosen, the conventional multilayer interdigital bandpass filter is designed. Table III shows the normalized element values from g_0 to g_5 for Chebyshev response.

TABLE III
NORMALISED ELEMENT VALUE

g_0	g_1	g_2	g_3	g_4	g_5
1.000	1.6703	1.1926	2.3661	0.8419	1.9841

The filter is designed based on method described in [12], [13]. The coupling coefficient, k is related as in (11).

$$k_{j,j+1}=\frac{w}{\sqrt{g_j g_{j+1}}} \tag{11}$$

where

w = fractional bandwidth

The mutual coupling matrix (M) can be calculated from equation (11) and then the physical size of the filter can be determined. The coupling matrix, M and external quality factors, Q_e of the filter obtained as follow:

$$[M]=\begin{bmatrix} 0 & 0.2757 & 0 & -0.0349 \\ 0.2757 & 0 & 0.2317 & 0 \\ 0 & 0.2317 & 0 & 0.2757 \\ -0.0349 & 0 & 0.2757 & 0 \end{bmatrix}$$

$$Q_{e1}=Q_{e4}=3.0462$$

From (12) the tapped point can be calculated [13] .

$$\frac{Q_e}{Z_0/Z_{01}}=\frac{\pi}{4\sin^2\left(\pi l/2L\right)} \tag{12}$$

$$Q_e=f_0/\Delta f_{\pm 90^\circ} \tag{13}$$

where

Z_0 = characteristic impedence of input and output line
Z_{01} = characteristic impedence of the resonators
Q_e = external Q of resonator
f_0 = center frequency
$\Delta f_{\pm 90^\circ}$ = bandwidth in which phase varies from -90° to +90°

After optimizing, the final dimension of the filter is obtained as shown in Fig. 2.

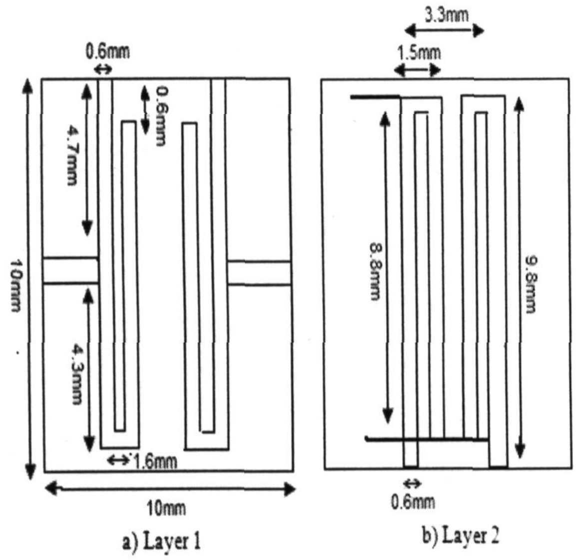

Fig. 2. Dimension of the interdigital bandpass filter

The bandpass filter structure as shown in Fig. 3 is a four pole cross-coupled interdigital bandpass filter. The bandpass filter consists of three layers of dielectric substrates. Each resonator with U-shape is a quarter-wavelength resonator. Roger RT Duroid 5870 is used as a substrate.

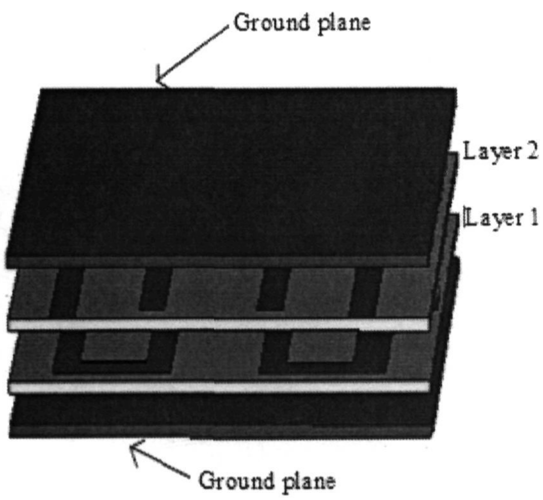

Fig. 3. A conventional four-pole multilayered interdigital bandpass filter

As shown in Fig 4, resonator 1 and 4 are arranged on the surface of the second layer of dielectric, while resonator 2 and 3 are on the first layer of the surface of the dielectric. The wide faces of resonator 1 and 2 as well as those of resonator 3 and 4, can be moved overlapped over each other or move apart from each other. As a result, either weak or strong couplings between resonators of different dielectric layer can be obtained readily. The bandpass filter is designed to have tapped-line input and output on the same plane, because it offers space and cost saving advantages [13].

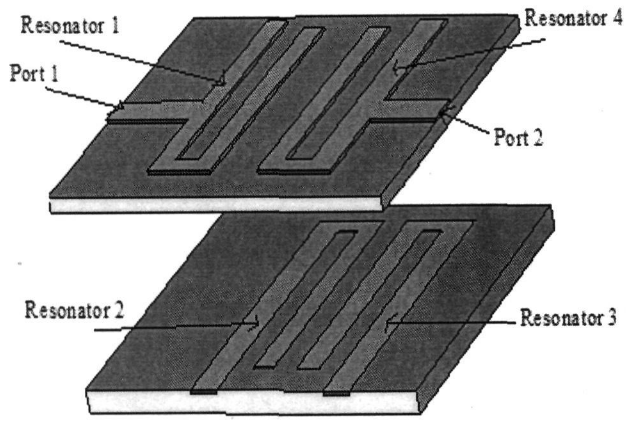

Fig. 4. Resonators for each layer of conventional bandpass filter

B. *Metamaterial Bandpass Filter Design*

The last step is to replace the substrate of conventional bandpass filter with the metamaterial S-structure. Four unit cells of metamaterial S-structure are used as a substrate for the conventional bandpass filter. The reason is because of the dimension of the slab is enough to act as substrate for the conventional bandpass filter. The slab of S-structure was shown in Fig. 5 below.

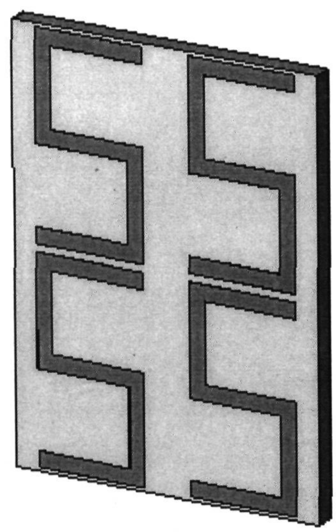

Fig. 5. A slab consist of 4 unit cells of S-structure

Transient solver mode in CST Microwave Studio was used to simulate this metamaterial bandpass filter.

.All the designed processes from start to the end are summarized in the flowchart below.

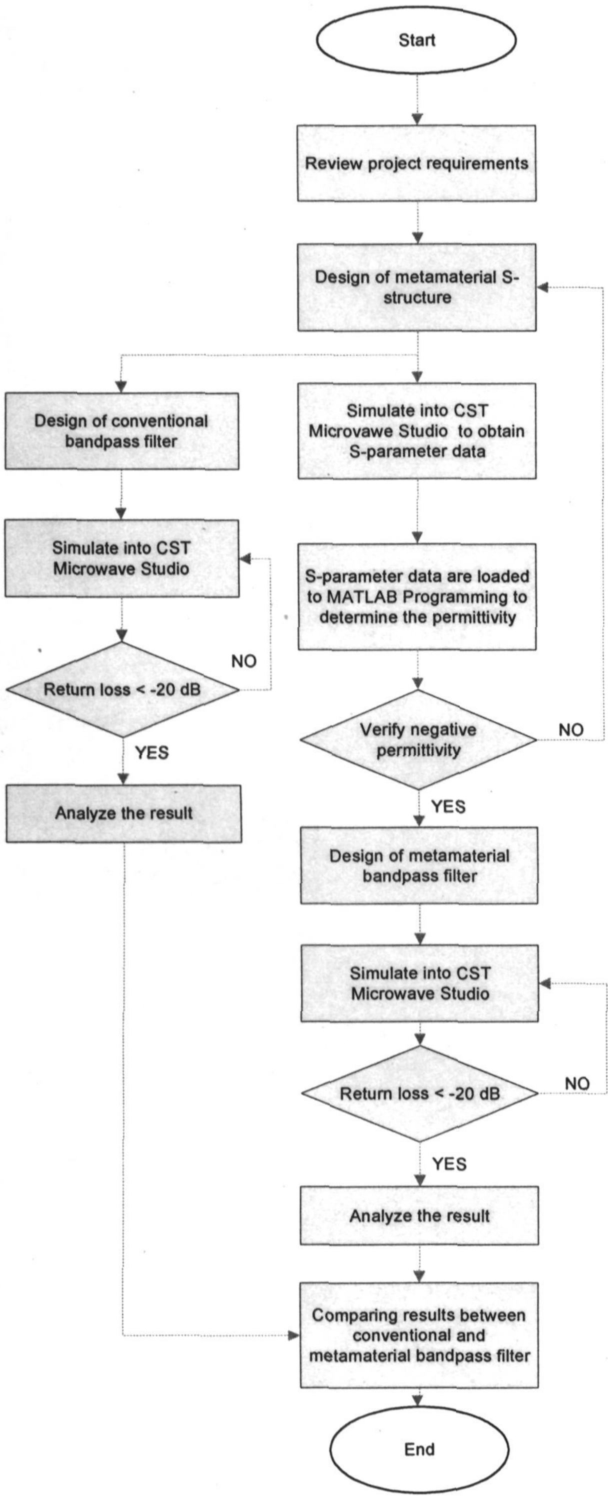

Fig. 6. Design procedure for conventional and metamaterial bandpass filter

III. Results and Discussion

Fig. 7 shows the output graph of MATLAB programming. It shows the value of negative permittivity occurred only at certain frequencies in which its nature is unpredictable. At 13.06 GHz which is the center frequency of the bandpass filter, it is observed that the permittivity is -5.18. Therefore, the simulated S-structure with negative permittivity has met the requirement of metamaterial as it performed one of the metamaterial behaviors.

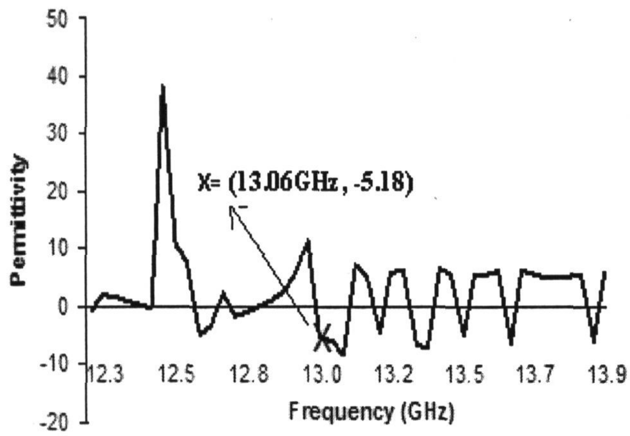

Fig. 7. The graph of permittivity vs frequency

For comparison purposes, Fig. 8 and Fig. 9 show the responses for both conventional bandpass filter and metamaterial bandpass filter respectively.

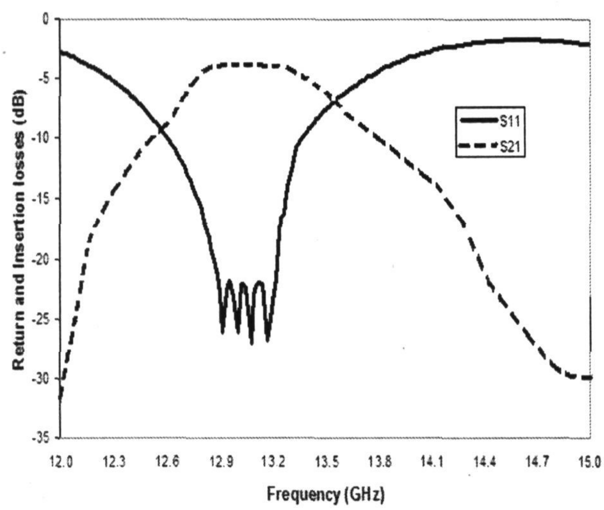

Fig. 8. Graph of S_{11} and S_{21} for conventional bandpass filter

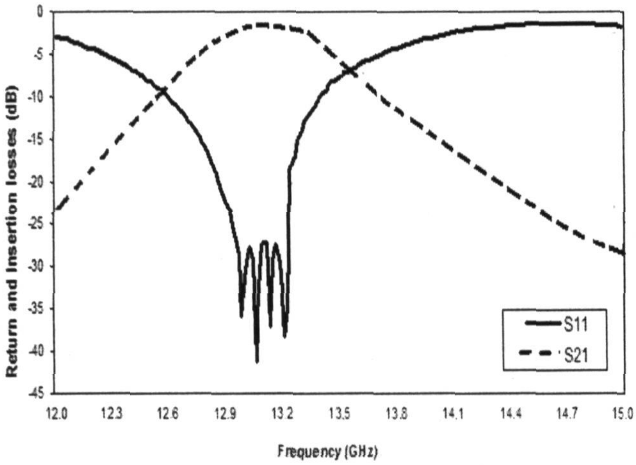

Fig. 9. Graph of S_{11} and S_{21} for metamaterial bandpass filter

In Fig. 10, at operating frequency, the return loss for conventional bandpass filter is -27.06 dB as compared to the metamaterial bandpass filter the return loss is -41.2 dB. A small return loss of metamaterial bandpass filter correspond precisely the power being delivered to the load. A high return loss of conventional bandpass filter correspond the power being reflected from the load and returning to the source. This is shown that the presence of metamaterial as a substrate can improve the return loss almost two times.

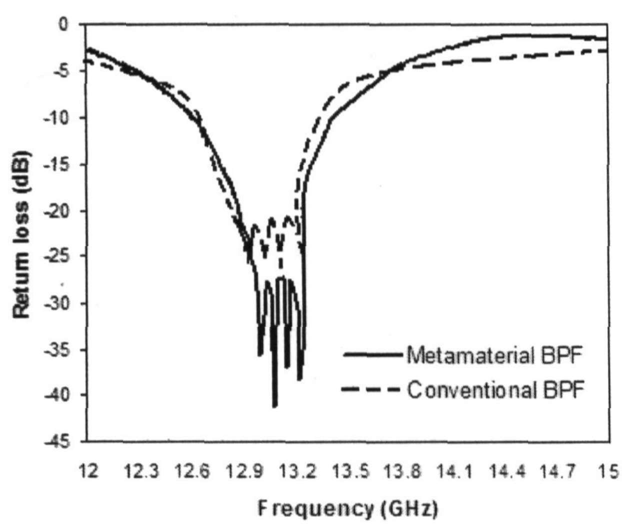

Fig. 10. Graph of S_{11} comparing conventional and metamaterial bandpass filter

As for insertion loss, S_{21} the metamaterial bandpass filter shows a better result rather than conventional bandpass filter. As shown in Fig. 11, at operating frequency the insertion loss for conventional and metamaterial bandpass filter is -3.7 dB and -1.53 dB respectively. Again it is proved that the presence of metamaterial can enhance the performance of insertion loss.

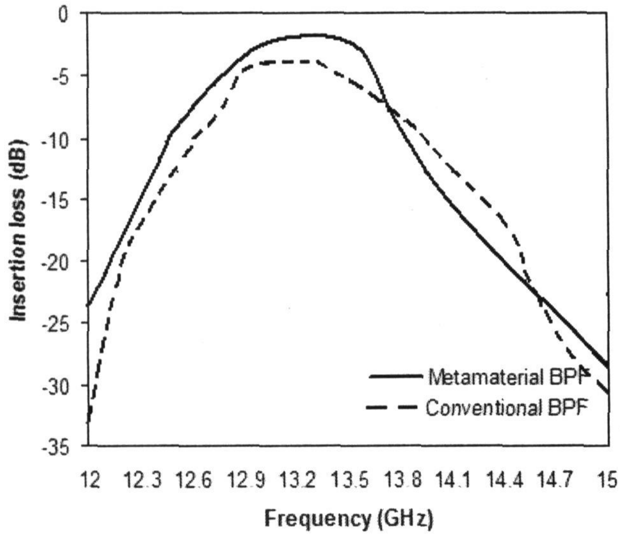

Fig. 11. Graph of S_{21} comparing conventional and metamaterial bandpass filter

From the insertion loss graph in Fig 11, the attenuation loss at stopband frequency, 14.7 GHz for conventional bandpass filter is -27.4dB and metamaterial bandpass filter is -23.5 dB. This again shows that the metamaterial can give a good performance by reducing the attenuation loss of the bandpass filter. As for bandwidth, the conventional bandpass filter provides 45% wider bandwidth than metamaterial bandpass filter.

Table IV shows the summarized data between the conventional bandpass filter and metamaterial bandpass filter. It is clearly shown that the presence of metamaterial has improved the performance for return loss, insertion loss and stopband attenuation loss. It also gives a narrow bandwidth for the metamaterial bandpass filter.

TABLE IV
COMPARISON RESULTS BETWEEN CONVENTIONAL AND METAMATERIAL BANDPASS FILTER

Description	Conventional bandpass filter	Metamaterial bandpass filter
Return loss,S_{11}	-27.06 dB	-41.2dB
Insertion loss, S_{21}	-3.7 dB	-1.53 dB
Stopband attenuation	-27.4dB	-23.5dB
Bandwidth	0.765 GHz	0.42 GHz

IV. CONCLUSION

The properties of metamaterial have been proven by showing negative permittivity of the material at certain range of frequencies. This negative permittivity can be obtained through metamaterial S-structure. The design procedures are also presented in this paper.

Based on the results that have been obtained from this project, it is proven that the metamaterial bandpass filter provides better results in term of return and insertion losses as well as stopband attenuation. The results have shown excellent performance of metamaterial bandpass filter over the conventional.

V. FUTURE DEVELOPMENT

The results can be improved in future in many ways. It is recommended that the metamaterial bandpass filter can be designed on different substrate with different properties and structure. Besides, different types of method instead using Nicholson-Ross-Weir (NRW) technique can be applied to determine the permittivity of metamaterial.

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