Hairpin Bandpass Filter On Metamaterial Substrate

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Abstract—**Recent developments of wireless communication systems demands an efficient bandpass filter (BPF) to select the required signal from the adjacent signals. Metamaterial bandpass filters are class of filters which use metamaterials to increase performance of miniaturized (electrically small) filter systems. In this paper a metamaterial hairpin BPF with defected ground structure was designed for center frequency of 2.3 GHz and 10% Fractional bandwidth (FBW) for WiMax application. The filters was simulated using CST MICROWAVE Studio® and Genesys Software on Rogers 3003 with ε_r = 3 and h = 0.5mm. Hairpin filter was designed on metamaterial properties to enhance the result of the conventional filter. The simulation and measured results will be used to analyze the s-parameter, bandwidth and size of the filter. The proposed approach improves the filter return loss by 38.51% and reduces the size of the device by 33.88%.**

***Key words*—defected ground structure (DGS), bandpass filter (BPF), Metamaterial,**

I. INRODUCTION

High performance and small size bandpass filters are essentially required in microwave communication systems to enhance the system performance and to reduce the fabrication cost. A bandpass filter will select certain range of frequency passes and the device rejects (attenuates) frequencies outside that range. The key features of a microstrip filter are relatively ease of construction, light weight, low cost, confortable to the mounting surface and extremely thin protrusion from the surface. The conventional design of the hairpin topology has the advantage of compact structure, but it has the limitation of wide bandwidth and poor skirt rate due to unavoidable coupling [6]. The advantage of microstrip filters makes them popular in many wireless applications [1-2].

Metamaterial hairpin BPF with DGS structure satisfies the need of low profile, light weight, and simple structure to assure reliability, mobility, and high efficiency characteristics.

Metamaterial is an artificial materials that exhibits negative permittivity ε, and negative permeability μ in certain frequency range which known as Left Handed Metamaterial (LHM) [4]. Although it is easier to realize metamaterials in microwave frequency region for negative refractions, there was still little progress toward practical applications [5].

The objective of this paper is to enhance, in a completely different approach, the s-parameter, and observe the bandwidth of conventional microstrip filter by applying the planar metamaterial patterned structures directly on ground plane of the filter, thus creating DGS on the filter.

The basic filter structure and its properties will be described in detailed. After scrutinizing the characteristics of the proposed structure in Section 2, the design steps will be explained in Section 3. A sample hairpin BPF for conventional and metamaterial were designed, and its simulated results were presented in Section 5. Finally, the measured result, discussion and the conclusions of this study will be highlighted in Section 6 and 7.

II. DESIGN OF THE HAIRPIN FILTER

A. Principle of filter design

In designing a microstrip filter, numerous substrates can be used to achieve good response and their relative permittivity is usually in the range of 2.2< ε_r <12. Ideally, the relative permittivity of dielectric substrate should be low (ε_r< 2.5), to enhance the fringing fields that account for the radiation. The most desirable substrate for a good filter performance is a thick substrate whereby the relative permittivity is at the lower end [5].

B. Design Specifications

By analyzing the microstrip filter, it was found that there are several types of parameter which needs to be considered. The return loss S_{11} in dB, insertion loss S_{21} in dB, and for the bandwidth as well as cut-off frequency. With this parameter, the microstrip filter will be easy to analyze and design for further improvements by adding DGS to enhance the return loss, pass band and the bandwidth of the filter. The parameters

Table 1: Parameters for the BPF

Parameter	Specification
Center Frequency	2.3Ghz
Fractional Bandwidth	10%
S11	> -20dB
Dielectric Substrate	Rogers RO 3003
Dielectric Constant	3
Substrate height, h	0.5mm
Copper thickness, t	0.035mm

III. MICROSTRIP HAIRPIN BANDPASS FILTER

Chebyshev filter has the best approximation to the ideal response filter for a specified order and ripple. The behavior and the performance of microstrip filter depends on the dimension that influences the operating frequency, cut-off, insertion loss and return loss. The design of Chebyshev hairpin microstrip BPF is initiated by determining the microstrip dimension. To determine the width, W, and the length, L of each element for 5th order microstrip, the value of impedances for each stage $Z_0 J_{i,i+1}$, have to be calculated:

$$FBW = \frac{\omega_2 - \omega_1}{\omega_r} \quad (1)$$

For the first coupling section:

$$Z_0 J_{0,1} = \sqrt{\frac{\pi(FBW)}{2 g_0 g_1}} \quad (2)$$

All intermediate section:

$$Z_0 J_{i,i+1} = \frac{\pi(FBW)}{\sqrt{2 g_n g_{n+1}}} \quad (3)$$

For final coupling section:

$$Z_0 J_{i,i+1} = \sqrt{\frac{\pi(FBW)}{2 g_n g_{n+1}}} \quad (4)$$

Where ω_2 and ω_1 is the upper and lower cut-off frequency of the band pass filter, and ω_r is the centre operating frequency.

Number of Elements n	g_1	g_2	g_3	g_4	g_5	g_6	g_7	
1	0.6986	1.0000						
2	1.4029	0.7071	1.9841					
3	1.5963	1.0967	1.5963	1.0000				
4	1.6703	1.1926	2.3661	0.8419	1.9841			
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000		
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841	
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1

Figure 1: Normalized Chebyshev filter element for 0.5dB passband ripple

The value of g_n were obtained from the table in Fig 1. For coupled microstrip lines, the even and odd modes impedance, Z0o and Z0e related to the admittance inverters $Z_0 J_{i,i+1}$ by the following equations where (Z_0=50Ω):

$$(Z0o)_{i,i+1} = Z_0 \left(1 + Z_0 J_{i,i+1} + \left(Z_0 J_{i,i+1}\right)^2\right. \quad (5)$$

$$(Z0e)_{i,i+1} = Z_0 \left(1 - Z_0 J_{i,i+1} + \left(Z_0 J_{i,i+1}\right)^2\right. \quad (6)$$

Table 2 shows the width, W, and separation, S, of each stage. By using microstrip calculator conversion from Genesys Software, the W and S for each couple elements can be obtain from the impedance value, $Z_0 J_{i,i+1}$ calculated earlier.

Table 2: Width, W, and Separation, S, used in the design

Stage	W (mm)	S (mm)
1	1.09	0.315
2	0.96	0.432
3	0.96	0.432
4	1.09	0.315

The hairpin filter configuration is derived from the edge coupled filter. To reduce the length and improve the aspect ratio, the resonators were folded into a "U" shape. Figure 2 below shows the fifth order hairpin filter configuration.

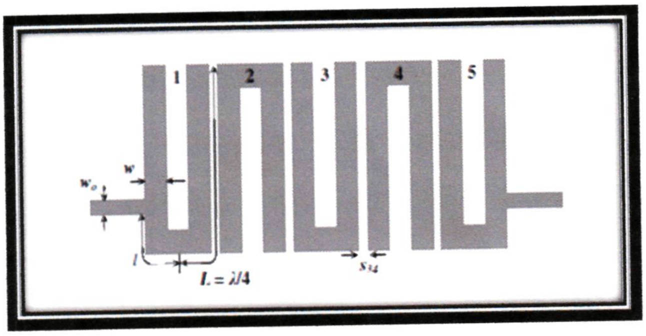


Figure 2: A five element tapped hairpin band pass filter

Q_{Lh} is the singly loaded Q for the first and the last resonators produced by tapping. The tap location l is measured from the short circuit end. Hence, the tap location, l, can be calculate using equation (7) to (10).

$$Q_{Lh} = \frac{g_1}{\Omega} = \frac{g_{n+1}}{\Omega} \quad (7)$$

$$\frac{l}{L} = \frac{2}{\pi}\sin^{-1}\sqrt{\frac{\pi\left(\frac{Z_o}{Z_{ol}}\right)}{2Q_{Lh}}} \quad (8)$$

Where Zo is the generator impedance (Zo=50Ω) and Z_{ol} is the internal filter impedance (Z_{ol}=70Ω).

$$L = \frac{\lambda_r}{4} \quad (9)$$

$$\lambda_r = \frac{\lambda_o}{\sqrt{\varepsilon_{re}}} \quad (10)$$

Where ε_{re} is the effective permittivity for Z=70Ω. Using equation (8), the tap location can be computed. The length, L and the tapered length, l as indicated in Fig 2 is 24.8mm and 12mm respectively. To obtain the resonant frequency of 2.3GHz, the width, W, and the length, L, of the overall filter are 78.5mm and 30.1mm as shown in Fig 3.

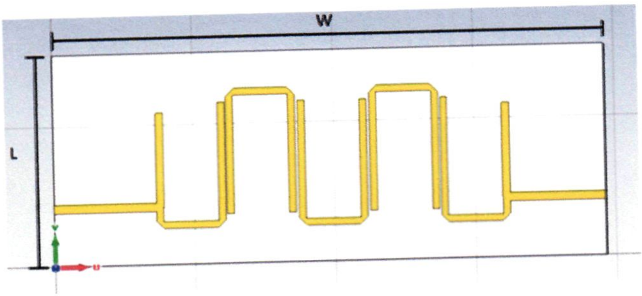


Figure 3: Conventional design of hairpin band pass filter

IV. METAMATERIAL TEST AND DGS DESIGN

To implement metamaterial as the substrate, the Nicholson Ross Weir (NRW) method is used. The overall dimension size of conventional hairpin bandpass filter were initially reduced 33.88% before applying NRW method. 50Ω straight line was design on top of the substrate as in Fig 4 with the length, X_L, is 62.7mm. The width of the 50Ω line that was obtained from CST calculator is 1.18mm. A dumbbell shaped DGS on the ground plane of the substrate (shape, size, position of the DGS pattern) is design and adjust by using the CST design suite software as shown in Fig 5. The result were then exported to the Microsoft Excel, a program to check and verify whether the design and point, produce negative value of permittivity and permeability (left handed material) of the substrate at the desire frequency of 2.3Ghz as shown in Fig 6.

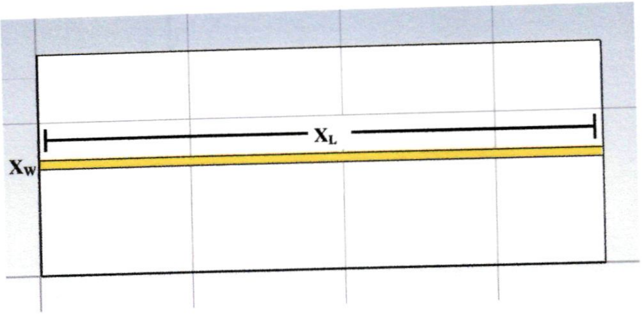


Figure 4: 50Ω line (the NRW test method)

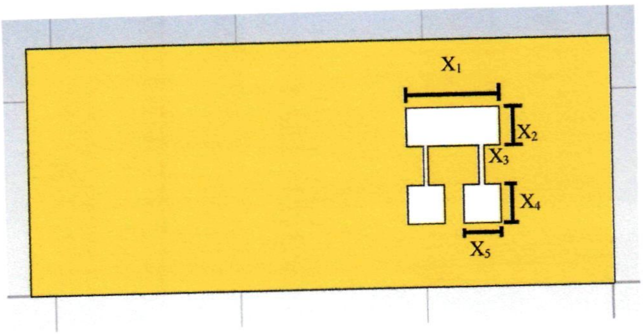
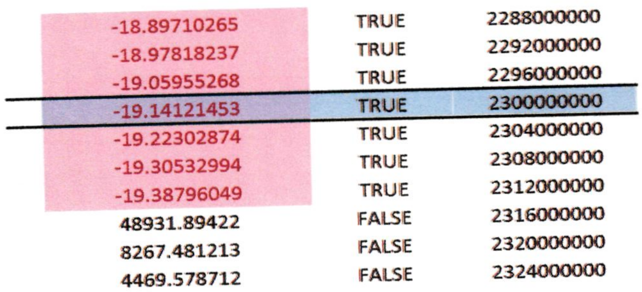


Figure 5: DGS design at the ground plane of the 50 ohm line

From Fig 5, the dimensions of X_1 = 10mm, and X_2, X_3 X_4 and X_5 are 4mm. The separation of the dumbbell is 2mm. The position of the DGS on the substrate will also affect the result in obtaining the meta-point.



-18.89710265	TRUE	2288000000
-18.97818237	TRUE	2292000000
-19.05955268	TRUE	2296000000
-19.14121453	TRUE	2300000000
-19.22302874	TRUE	2304000000
-19.30532994	TRUE	2308000000
-19.38796049	TRUE	2312000000
48931.89422	FALSE	2316000000
8267.481213	FALSE	2320000000
4469.578712	FALSE	2324000000

Figure 6: Check result through Microsoft Excel software

After the NRW method were used and the desired result were achieved, the design is then were checked using the Microsoft Excel program to prove whether the point of the DGS is at the desired frequency change the permittivity and the permeability of the substrate to negative value in Figure 6. Then, the designed filter was implemented on top of the DGS designed by replacing the 50Ω line.

Table 2: Hairpin Band Pass Filter Dimension

	Conventional (mm)	Metamaterial (mm)
Width	78.5	62.7
Length	30.2	25
Total Dimension	78.5 x 30.2	62.7 x 25

V. SIMULATION RESULT OF THE FILTER

From the design, conventional and the metamaterial hairpin BPF were then simulated using CST microwave studio software. The characterization of the BPF includes the investigation of parameters such as return loss, insertion loss, cut-off frequency and bandwidth calculation.

C. Insertion Loss, Return Loss, and Bandwidth

The simulation result of return loss and insertion loss from both conventional and metamaterial microstrip hairpin BPF along the targeted frequency range are shown in Fig 7, and Fig 8, respectively.

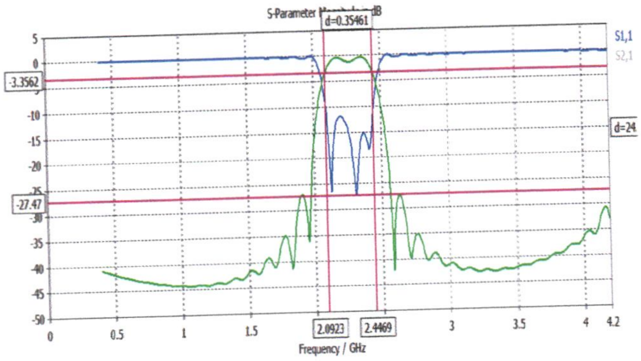


Figure 7: Magnitude (dB) vs. Frequency (GHz) of conventional hairpin BPF

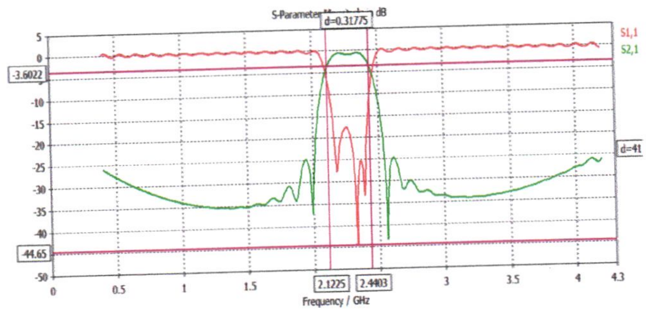


Figure 8: Magnitude (dB) vs. Frequency (GHz) of metamaterial hairpin BPF

Figure 7 and shows the resonant frequency of the conventional BPF was at 2.31GHz with the value of return loss was -27.41dB which met the specification of the WiMax application. Bandwidth of the filter is calculated from -3dB of the maximum value of insertion loss. Hence, the bandwidth was 355MHz. The bandwidth slightly differs from the targeted value but it is still in an acceptable range.

The resonant frequency of the metamaterial BPF in Fig 8 was 2.33GHz, with the value of return loss was -44.58dB. From the return loss graph, the design of the metamaterial filter value is lower than the conventional filter. This can be clearly seen from Fig 9, the comparison between conventional and metamaterial return loss.

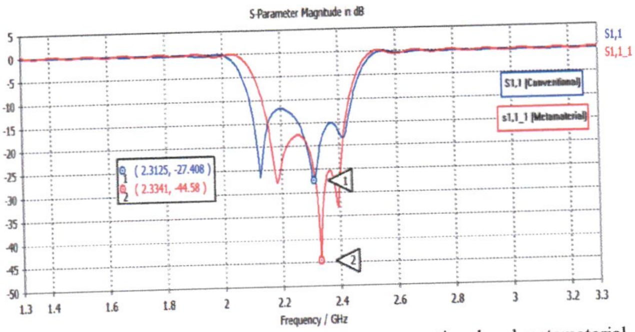


Figure 9: Return loss Comparison between conventional and metamaterial hairpin BPF

From Fig 7 and Fig 8, the bandwidth of both BPFs can be determined. By observing the graph in Fig 7, it is shown that the metamaterial filter enhance the return loss value of the filter from -27.408dB to -44.58dB, a difference of of 38.51%. The insertion loss response from metamaterial filter improves as the graph is smoother and there are fewer ripples at the stop band region. The minimum values of metamaterial return loss slightly shifted to 2.33GHz. Theoretically for metameterial, the graph will shift to the left when the size of filter is reduced [10]. Due to the limitation of fabrication, the minimum dimension of 0.3mm, any smaller dimension than that value cannot be fabricated.

The results were then tabulated as in Table 3 to show the comparison between the conventional and metamaterial BPF in terms of S-parameter magnitude, bandwidth and the percentage of differences.

Table 3: Comparison between conventional and metamaterial hairpin BPF performance

	Conventional	Metamaterial	Differences (%)
Filter Dimensions	78.5mm X 30.2mm	62.7mm X 25mm	33.88
S-parameter magnitude (dB)	-27.408	-44.58	38.51
Bandwith (Ghz)	0.355	0.318	10.32

This result clearly shows that the DGS structure employed on the ground plane of the filter, the metamaterial characteristics were achieved, thus improving the return loss and insertion loss of the conventional filter at the same resonant frequency while reducing the dimension of the filter.

VI. MEASUREMENT RESULT AND DISCUSSION

The conventional BPF and the metamaterial BPF with DGS were then deployed on a double-sided Rogers RO 3003 substrate with ε_r = 3 and the thickness of 0.5mm. The filter was connected to a connector of 50Ω. Fig 10 and 11 shows the complete design of the proposed conventional and the reduced size metamaterial filter with DGS after the fabrication.

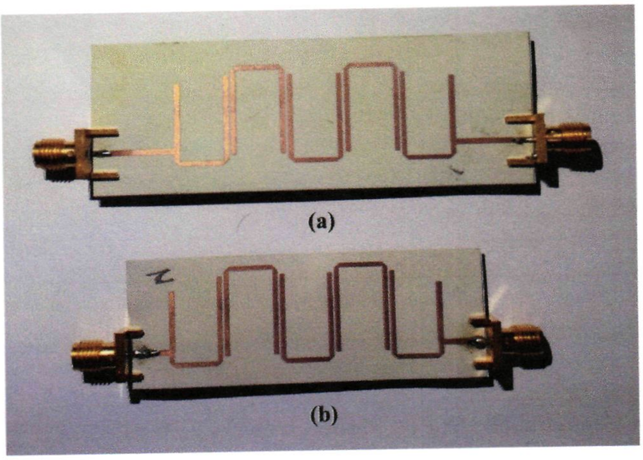


Figure 10: Top view of (a) Conventional BPF and (b) Metamaterial BPF

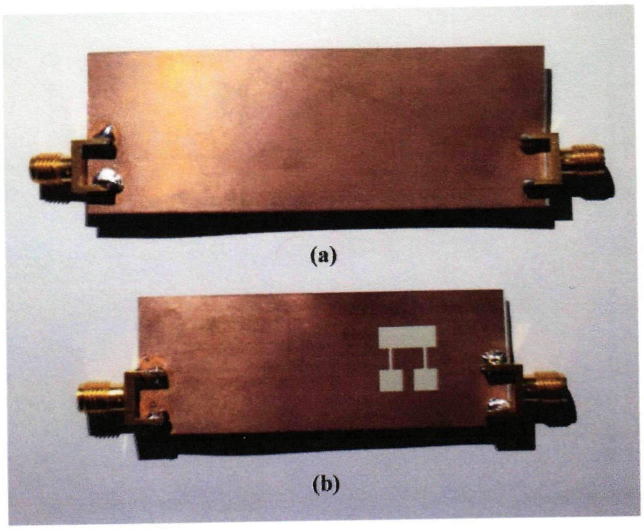


Figure 11: Bottom view of (a) Conventional BPF and (b) Metamaterial BPF

A. *Measured return loss S_{11} in dB.*

Both of the proposed filters then have been measured using the Vector Network Analyzer (VNA). The result from the measurement then was exported from the VNA and displayed through Genesys Software.

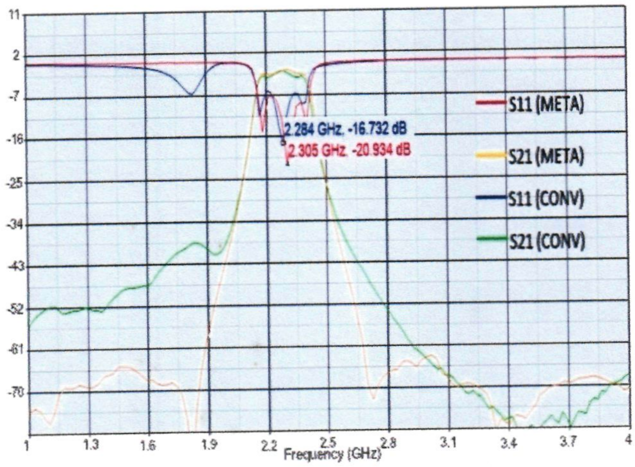


Figure 12: Measurement result from both microstrip BPFs

From figure 12, it is shown that the metamaterial filter performs better than the conventional filter. The return loss of the metamaterial filter is lower than the conventional filter, such as in the simulation result. Both conventional and metamaterial filters have return loss is higher than the simulation result by 37% and 52%. This is due to the limitation of the fabrication where it can only be fabricated for the smallest size of microstrip line of 0.3mm, thus the actual microstrip size from simulation had to be round-up to one decimal places. From the measurement result, it can be noted that the resonant frequency of the filter is slightly shifted to the left. Besides that, the measurement result for insertion loss is not as smooth as the simulation results. Since the simulation filter was designed in a perfect condition, these ripples and spikes were expected since the existence of external disturbance in measurement area such as mobile phones, people and other objects. The thickness of the filter that is very thin (0.5mm), makes the filter fragile and slightest of movement or bends will affect the measurement result.

VII. CONCLUSION

The design and characterization of conventional BPF and metamaterial hairpin BPF for 2.3GHz have been demonstrated. Both filters deployed on a double-sided Rogers RO 3003 substrate with ε_r of 3 and thickness of 0.5mm. The characteristic performance of conventional and metamaterial BPF have been investigated and compared. It has been shown that the metamaterial microstrip filter has better return loss value than the conventional microstrip filter. The result clearly shows that applying mematerial will change the nature of the substrate by implementing DGS can improve the nature of the filter while reducing dimension sizes.

FUTURE DEVELOPMENT

This section mainly consists of two parts which is the research that was done earlier as experiment and other recommendations for future work regarding metamaterial. The design of filters can be further improve by using higher substrate thickness. Adding an aluminum plate at the ground of filter provides better grounding and stabilizes the structure. In term of DGS, different shapes of DGS can be developed to operate at different frequency. Besides that, by implementing metamaterial concept, other microwave devices such as antenna and amplifiers can also be improve in terms of dimension and performance.

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