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Λ-type 5.75GHz Chebyshev Bandpass Filter for WLAN Applications

Veeraiyah Thangasamy[1], Shankar Duraikannan[2]

Lecturer, School of Engineering, Asia Pacific University, Kuala Lumpur, Malaysia.[1, 2]

ABSTRACT:This paper presents the design and evaluation of Λ-type 5.75GHz Chebyshev bandpass filter aimed at reduction of the filter size used for WLAN applications. The proposed filter structure is realized with two different materials Roger Duroid (TLY-5A) and FR4 to have a pass band centered at 5.75GHz with a bandwidth of 100MHz. The performances of designed filter structures are evaluated in comparison with the conventional filter structure. Results shows that the performance of Λ-type filer structure realized using TLY-5A is promising with a size reduction of 51% compared to conventional filter structure.

Keywords: RF Filters; Chebyshev Filters; WLAN Filters; TLY-5A.

I. INTRODUCTION

Radio Frequency (RF) and microwave filters were developed since World War II [1]. Thereafter a variety of structure has been demonstrated by researchers in terms of filter compactness and frequency selectivity. Parallel coupled line, comb line, inter digital and hairpin line are significant designs of band pass and band stop filters which shows a good response, however robust and efficient filter structures are need of the hour[2].

Filter plays a significant role in radio frequency and microwave communication systems. Wideband applications requires coupled line microstrip and stripline filters because the demand on selectivity is not severe. On the other hand, wireless applications need miniature filters due to space and cost constraints. There by size reduction has becoming a major consideration for practical application in broadband wireless access communication system. However, the performance of the filter must not be influenced by the reduction in size and the designed compact filter should achieve fine system performances such as good bandwidth, low return loss and accurate centerfrequency [2].

The electrical performances of the filter are described in terms of insertion loss, return loss, frequency selectivity or attenuation at rejection band, group delay variation in the passband. Filters are required to have small insertion loss and large return loss for good impedance matching with interconnecting components, and high frequency selectivity to prevent interference. In mechanical performance aspect, filters are required to have small volume, mass and good temperature stability [2-4].

II. REVIEW OF MINIATURIZED BAND PASS FILTERS

The filter design belong to early time in 1915 when Wagner in Germany and Campbell in the United States came up with an idea of “Electric wave filters” based on lumped approximations to transmission lines. In the 1920s Zobel at Bell Laboratories published a filter design using image parameter technique. Around 1940, Darlington and Cauer extended earlier theories to exactly synthesize network to prescribed transfer functions. Due to the significant computational requirement, these methods remained primarily of academic interest until digital computers were used to synthesize low pass prototype, from which other filter structures were derived. These low pass prototype have been tabulated for many filter transfer functions named after the mathematicians involved in the development of the polynomials, such as Butterworth, Chebyshev, Bessel and others. Thereafter several minimization techniques were proposed by several researches. The minimization is achieved using techniques like spurious response suppression, design using open stub for perturbation for the multimode operation and zero point generation at the stop band control stepped impedance

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resonators and inter-digital coupling structures, signal interference technique and shape modification using quarter wave stub etc. [1 – 10].

III. DESIGN PERSPECTIVES OF CHEBYSHEV BAND PASS FILTER

Chebyshev filter exhibits a better performance compared to Butterworth filter in terms of frequency response [3-5]. The insertion loss method which is the most commonly used method is adopted in the design as the network synthesis characteristics allows accuracy in frequency response analysis. Fig. 1 represents the process of filter realization.

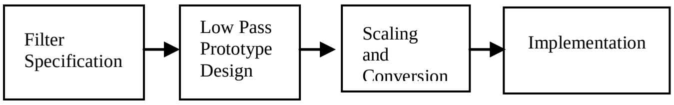

Fig. 1: Block diagram of insertion loss method [3].

The design starts with the filter specifications and continued with low pass filter prototype that is to normalize in term of impedance and frequency. The low pass filter can be converted into other desired frequency range and impedance level through transformation. Scaling and conversion are used to design high pass, band pass and band stop filter [3].

The design is initiated with a low pass prototype which is a passive, reciprocal low loss two port network, designed to operate from 1Ω generator into a 1Ω load. The filter response has a low pass characteristic with its pass band-edge frequency at ω = 1[3].

The element values for Chebyshev filter with $g_o = 1$, $\omega_1 = 1$ with a ripple of 0.5dB are shown in Table 1 below. The numbers of orders denoted by N are from 1 to 9 [3].

Table 1: Element values for Chebyshev filter with ripple = 0.5dB, $g_0 = 1, \omega_1 = 1$

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
1	0.6986	1.000								
2	1.4029	1.7071	1.9841							
3	1.5963	1.0967	1.5963	1.000						
4	1.6703	1.1926	2.3661	0.8419	1.9841					
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.000				
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	1.3583	1.7372	1.000		
8	1.7504	1.2647	2.6567	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841	
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.000

Scaling and Conversion: For the scaling process we consider scaling of the following parameters namely impedance and frequency scaling. By combining both the impedance and frequency scaling the new element value will be as expressed in (1) and (2).

$$L'_k = \frac{R_o L_k}{\omega_c} \tag{1}$$

$$C'_k = \frac{C_k}{R_o \omega_c} \tag{2}$$

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Conversion: A transformation is required to convert the filter design from the low pass filter to band pass filter. This is achieved by the following conversion.

$$\omega = \frac{1}{\Delta}\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right) \quad (3)$$

For $\omega = 1$ and $\omega = -1$ to map to ω_1 and ω_2 then

$$1 = \frac{1}{\Delta}\left(\frac{\omega_1}{\omega_o} - \frac{\omega_o}{\omega_1}\right) \quad (4)$$

$$-1 = \frac{1}{\Delta}\left(\frac{\omega_2}{\omega_o} - \frac{\omega_o}{\omega_2}\right) \quad (5)$$

The frequency tends to shift from low pass to band pass as shown in Fig. 2.

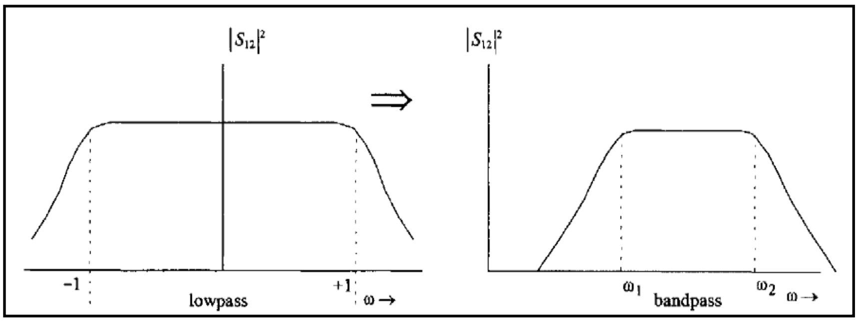

Fig. 2: Conversion of low pass filter to band pass filter [6]

By applying the transformation to the inductor, the inductor gets converted to series combination of inductor and capacitor and by applying the transformation to the capacitor the capacitors gets converted to parallel combination of inductors and capacitors.

$$Z = j\omega L = \left(\frac{jL}{\Delta\omega_o}\right)\omega - \left(\frac{j}{\omega\frac{\Delta}{L\omega_o}}\right) \quad (6)$$

$$Z = j\omega C = \left(\frac{jC}{\Delta\omega_o}\right)\omega - \left(\frac{j}{\omega\frac{\Delta}{C\omega_o}}\right) \quad (7)$$

Filter Realization: The filter is realized using microstrip transmission line. Fig. 3 is the basic microstrip parallel coupled line coupler. The characteristic impedance Z_o of the micro strip is

$$Z_o = \begin{cases} \frac{60}{\sqrt{\varepsilon_e}}\ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & for\frac{W}{d}\langle 1 \\ \frac{120\pi}{\sqrt{\varepsilon_e\left[\frac{W}{d} + 1.393 + 0.667\ln\left(\frac{W}{d} + 1.444\right)\right]}} & for\frac{W}{d}\rangle 1 \end{cases} \quad (8)$$

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It is easy to fabricate multi-section parallel coupled line band pass in microstrip technology with bandwidth less than that of 20%. As the bandwidth of the filter gets wider, it becomes difficult to fabricate because the coupled line are required to get more closely to each other. Parallel coupled line filter has properties of superposition of even and odd mode excitations [6-8].

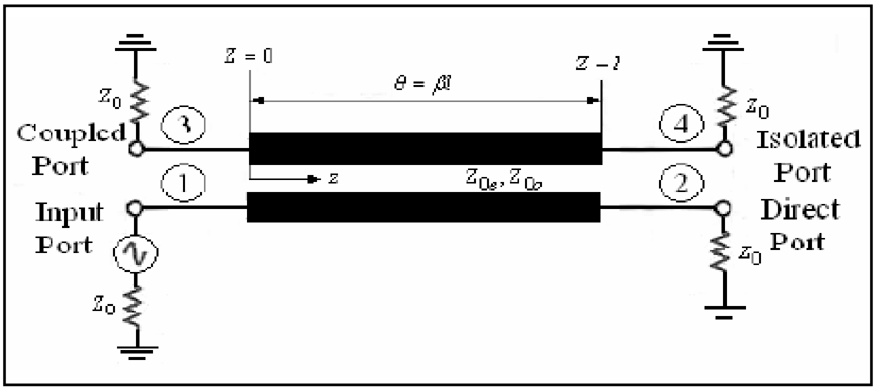

Fig. 3: Microstrip parallel coupled line coupler[8]

In order to design a narrow band pass filters, number of coupled line are cascaded as indicated in Fig. 4. Even and old impedances are denoted are Z_{Oe} and Z_{Oo} respectively. The values of Zo should be around 50Ω since they represent the input and output. Hence they are matched by SMA connectors [8].

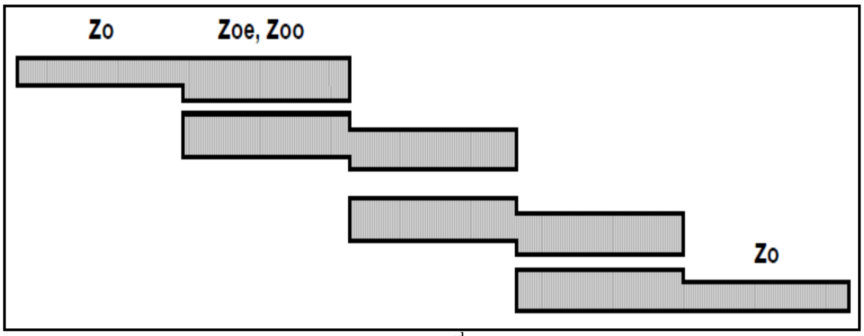

Fig. 4: Cascaded coupled 3rd order band pass filter.

$$Z_o J_1 = \sqrt{\frac{\Delta\pi}{2g_1}} \quad (9)$$

$$Z_o J_n = \sqrt{\frac{\Delta\pi}{2g_{n-1}g_n}} \quad for\ n = 2,3,\ldots N \quad (10)$$

$$Z_{oe} = Z_o\left[1 + JZ_o + (JZ_o)^2\right] \quad (11)$$

$$Z_{oo} = Z_o\left[1 - JZ_o + (JZ_o)^2\right] \quad (12)$$

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IV. DESIGN SPECIFICATIONS

In filter design the most important thing to be considered is the specification such as center frequency, bandwidth, insertion loss, stop band attenuation and the ripple of the desired filter. The filter specifications listed in Table 2 are with reference to the RF filter specifications proposed for WLAN applications [4].

Table 2: Specification of filter for WLAN[4]

Specifications	Desired Values
Center Frequency	5.75 GHz
Bandwidth	100MHz
Insertion Loss	Less than -10 dB
Stop Band Attenuation	25dB at 2.85GHz
Ripple	0.5 dB

Defined with the specifications of the filter design the order of the filter should be determined. The order of the filter is computed as

$$n \geq \frac{\log(X + \sqrt{X^2 + 1}}{\log(\omega_n + \sqrt{\omega^2 - 1}} \qquad (13)$$

$$X = \sqrt{\left(10^{0.1\alpha p} - 1\right)^{-1}\left(10^{0.1\alpha s} - 1\right)} \qquad (14)$$

Pass band ripple p= 0.5 dB and the stop band ripple s= 0.25 dB, therefore X = 50.828 and n $\geq$ 8.55 = 9

The normalized parameter of the 9th order Chebyshev filter lumped elements is then determined based on the element value for ripple low pass filter prototype at 0.5dB ripple.

Table 3: 9th order element values for equal ripple low pass filter at 0.5dB

n	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.000

The coupled line are calculated as Z_oJ_1 = 0.1641, Z_{oe} = 59.5500, Z_{oo} = 43.1422, with the consideration of n = 1 Δ = 0.03 and g_1=1.7504 F. And the final values of the even and odd impedance are determined as listed in Table 4.

Table 4: Even and odd impedance of 9th order filter

N	g_n	Z_oJ_n	$Z_{0e}(\Omega)$	$Z_{0o}(\Omega)$
1	1.7504	0.1641	59.5500	43.1422
2	1.2690	0.0316	51.6309	48.4691
3	2.6678	0.0256	51.3134	48.7522
4	1.3673	0.0247	51.2641	48.7968
5	2.7239	0.0244	51.2507	48.8089
6	1.3673	0.0244	51.2507	48.8089
7	2.6678	0.0247	51.2641	48.7968
8	1.2690	0.0256	51.3134	48.7522
9	1.7540	0.0316	51.6309	48.4691
10	1.0000	0.1641	59.55	43.1422

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V. RESULTS AND DISCUSSION

A. Conventional 9th Order Chebyshev Band Pass Filter

The schematic of the 9th order conventional Chebyshev band pass filter is shown in Fig. 5. The dielectric constant and loss tangent of the structuremodelled using TLY-5A were 2.16 and 0.0009 respectively with a substrate thickness of 0.508mm .Next FR4 was used as a substrate. The dielectric constant and loss tangent of FR4 were 5.2 and 0.019 respectively with a substrate thickness of 1.6mm.

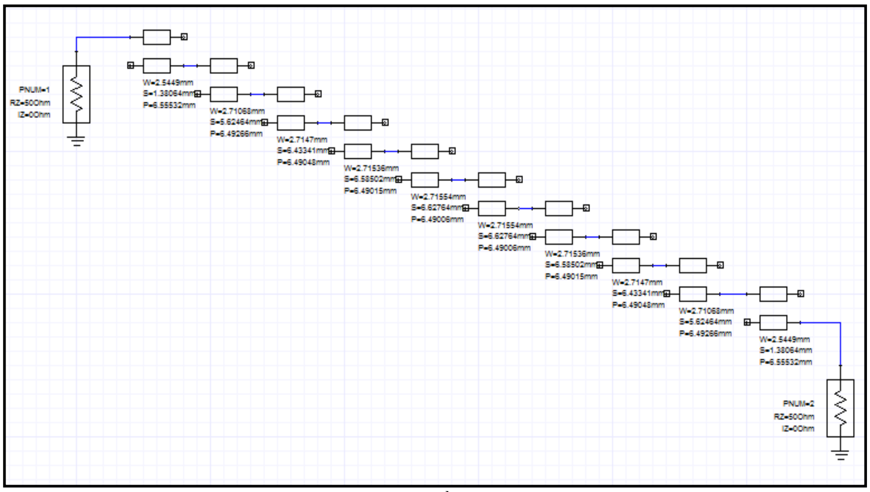

Fig 5: Schematic of conventional 9th order Chebyshev bandpass filter

The physical length (P) width (W) and separation (S) were determined by simulation using Ansoft Designer SV for TLY-5A and FR4 as stated in Table 5 and 6.

Table 5: Dimension of L, W, S for TLY – 5A

N	g_n	Z_oJ_n (Ω)	Z_{oe} (Ω)	Z_{oo} (Ω)	W (mm)	S (mm)	P (mm)
1	1.7504	0.1641	59.5500	43.1422	1.4536	0.3433	9.6394
2	1.2690	0.0316	51.6309	48.4691	1.5586	1.7141	9.5768
3	2.6678	0.0256	51.3134	48.7522	1.5615	1.9615	9.5757
4	1.3673	0.0247	51.2641	48.7968	1.5619	2.0072	9.5755
5	2.7239	0.0244	51.2507	48.8089	1.5620	2.0200	9.5754
6	1.3673	0.0244	51.2507	48.8089	1.5620	2.0200	9.5754
7	2.6678	0.0247	51.2641	48.7968	1.5619	2.0072	9.5755
8	1.2690	0.0256	51.3134	48.7522	1.5615	1.9615	9.5757
9	1.7540	0.0316	51.6309	48.4691	1.5586	1.7141	9.5768
10	1.0000	0.1641	59.5500	43.1422	1.4536	0.3433	9.6394

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Table 6: Dimension of L, W, S for FR4

N	Gn	ZoJn (Ω)	Zoe (Ω)	Zoo (Ω)	W (mm)	S (mm)	P (mm)
1	1.7504	0.1641	59.5500	43.1422	2.5449	1.3806	6.5553
2	1.2690	0.0316	51.6309	48.4691	2.7107	5.6246	6.4927
3	2.6678	0.0256	51.3134	48.7522	2.7147	6.4334	6.4905
4	1.3673	0.0247	51.2641	48.7968	2.7154	6.5850	6.4902
5	2.7239	0.0244	51.2507	48.8089	2.7155	6.6276	6.4901
6	1.3673	0.0244	51.2507	48.8089	2.7155	6.6276	6.4901
7	2.6678	0.0247	51.2641	48.7968	2.7154	6.5850	6.4902
8	1.2690	0.0256	51.3134	48.7522	2.7147	6.4334	6.4905
9	1.7540	0.0316	51.6309	48.4691	2.7107	5.6246	6.4927
10	1.0000	0.1641	59.5500	43.1422	2.5449	1.3806	6.5553

Comparing W and S of TLY-5A and FR4 the dimension of FR4 is greater compared to TLY-5A. However if P is compared the FR4 is smaller compared to TLY-5A which eventually makes FR4 smaller in length compared to TLY-5A. From simulation layout of TLY-5A and FR4 as indicated in Fig. 6 and 7, it is clear that compared to TLY-5A, FR4 is smaller in length whereas the width of separation is greater.

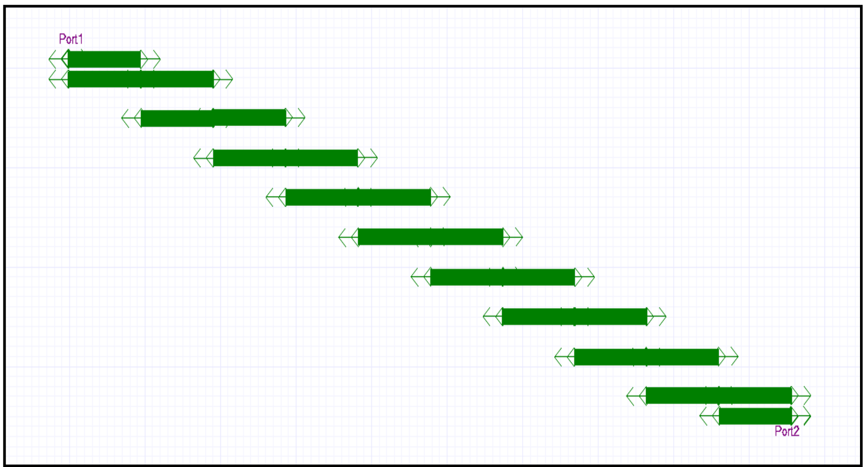

Fig. 6: Layout of conventional 9th order Chebyshev bandpass filter using TLY-5A

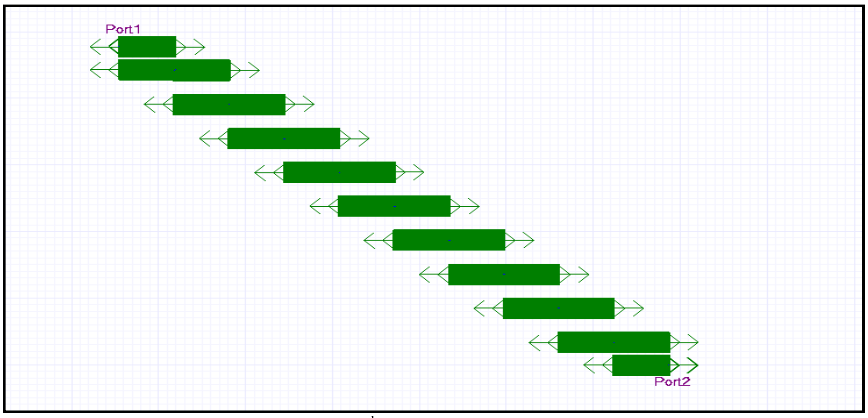

Fig. 7: Layout of conventional 9th order Chebyshev bandpass filter using FR4.

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Fig. 8 and 9 show the frequency responses for TLY-5A and FR4 respectively. The red color line represents the Return Loss (S_{11}) and the blue line represents the Insertion Loss (S_{21}).Table 7 is the comparative analysis of theoretical and experimental result from Fig. 8 and 9. The insertion loss of the substrate TLY-5A did achieve its expected target with a value of -4.59dB whereas for FR4 the results are nowhere near the target with a value of -37.37dB with a difference of around 27dB. The return loss for TLY-5A did achieve the targeted values; however for FR4 it has not achieved the target.

Table 7: Comparison theoretical and simulation results of conventional 9th order band pass filter design using TLY-5A and FR4

Design Specifications	Expected Results	TLY-5A Simulated Results	FR4 Simulated Results
Cut Off Frequency	5.75 GHz	5.75 GHz	5.75 GHz
Insertion Loss, S_{21}	< -10 dB	-4.59 dB	-37.37 dB
Return Loss, S_{11}	>-10 dB	-12.08 dB	-9.42 dB
Bandwidth	100 MHz	165 MHz	92 MHz

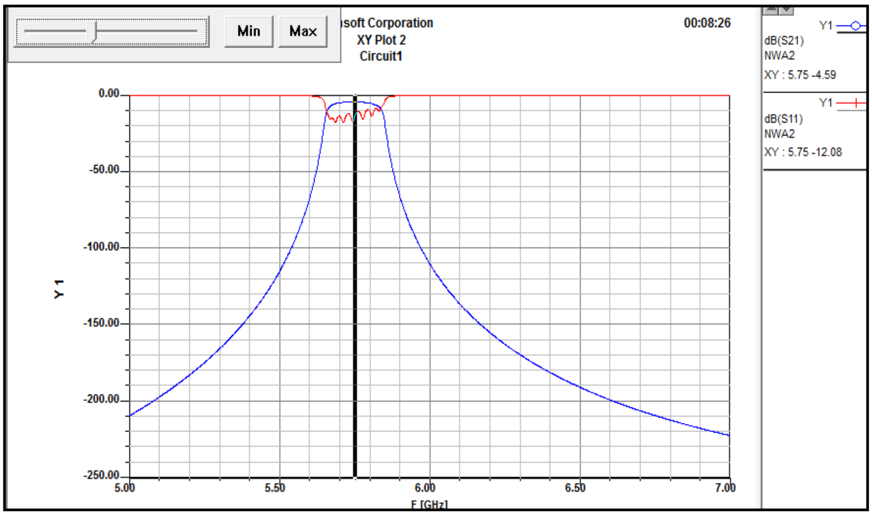

Fig. 8: Frequency response of TLY-5A band pass filter

Focusing on bandwidth of the conventional band pass filter designed on substrate TLY-5A is wider than that of the expected results by 65 MHz while the bandwidth of the filter simulated from FR4 is narrower by 8MHz compared to the expected results.

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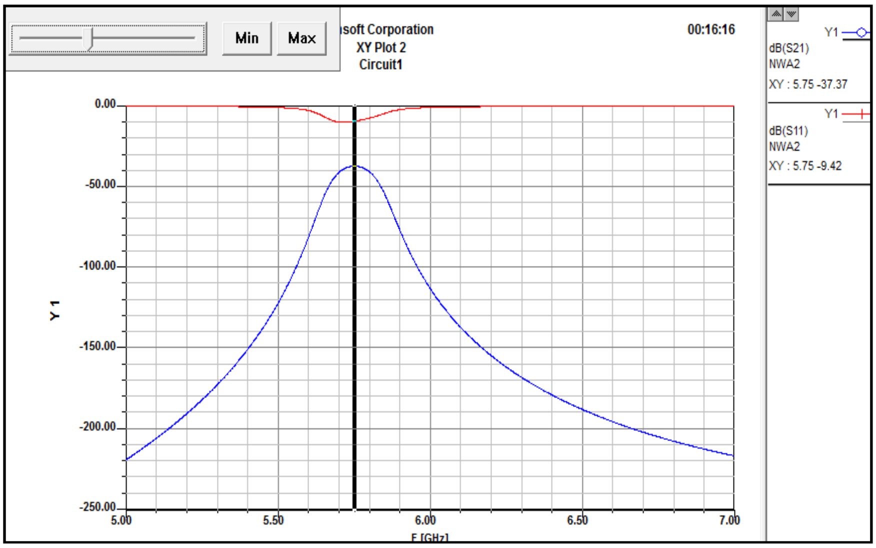

Fig. 9: Frequency Response of FR4 Band Pass Filter

After a good observation of the conventional type result, optimization is needed in order to achieve the target values. Optimization is based on parameter study (trial and error method) where the W, S and P parameters are changed until a desired value is yielded. It is advised to change one parameter at a time so that one can notice the effect of each parameter. The FR4 filter needs more optimization since its insertion loss is drifted far away compared to that of TLY-5A.

Table 8 and 9 is the optimized values for both TLY-5A and FR4 substrates. The width, space and physical length of each coupled lines should be approximately the same except for the first and last coupled lines to match the input and output of the Chebyshev band pass filter. This in turn will give rise to the return loss (S_{11}).

Table 8: Optimization values of W, S and P for TLY-5A

n	Gn	ZoJn (Ω)	Zoe (Ω)	Zoo (Ω)	W (mm)	S (mm)	P (mm)
1	1.7504	0.1641	59.5500	43.1422	1.5607	0.4528	9.5744
2	1.2690	0.0316	51.6309	48.4691	1.5634	2.3423	9.5744
3	2.6678	0.0256	51.3134	48.7522	1.5656	2.4784	9.5748
4	1.3673	0.0247	51.2641	48.7968	1.5659	2.4219	9.5767
5	2.7239	0.0244	51.2507	48.8089	1.5661	2.4341	9.5767
6	1.3673	0.0244	51.2507	48.8089	1.5661	2.4341	9.5767
7	2.6678	0.0247	51.2641	48.7968	1.5659	2.4219	9.5767
8	1.2690	0.0256	51.3134	48.7522	1.5656	2.4784	9.5748
9	1.7540	0.0316	51.6309	48.4691	1.5534	2.3423	9.5744
10	1.0000	0.1641	59.5500	43.1422	1.5607	0.4528	9.5744

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Table 9: Optimized values of W, S and P for FR4

n	**Gn**	**ZoJn (Ω)**	**Zoe (Ω)**	**Zoo (Ω)**	**W (mm)**	**S (mm)**	**P (mm)**
1	1.7504	0.1641	59.5500	43.1422	3.0871	0.3422	6.5065
2	1.2690	0.0316	51.6309	48.4691	3.0874	2.0312	6.5004
3	2.6678	0.0256	51.3134	48.7522	3.0816	2.0339	6.5089
4	1.3673	0.0247	51.2641	48.7968	3.0823	2.0384	6.5005
5	2.7239	0.0244	51.2507	48.8089	3.0825	2.0318	6.5086
6	1.3673	0.0244	51.2507	48.8089	3.0825	2.0318	6.5086
7	2.6678	0.0247	51.2641	48.7968	3.0823	2.0384	6.5005
8	1.2690	0.0256	51.3134	48.7522	3.0816	2.0339	6.5089
9	1.7540	0.0316	51.6309	48.4691	3.0874	2.0312	6.5004
10	1.0000	0.1641	59.5500	43.1422	3.0871	0.3422	6.5065

Fig. 10 is the frequency response of band pass filter of TLY-5A. The insertion loss S_{21} is -5.97dB whereas the return loss S_{11} is -15.10dB. The filter operates ata operates at a bandwidth of 100 MHz from 5.7 to 5.8 GHz. The optimization in TLY-5A contributes to target values.

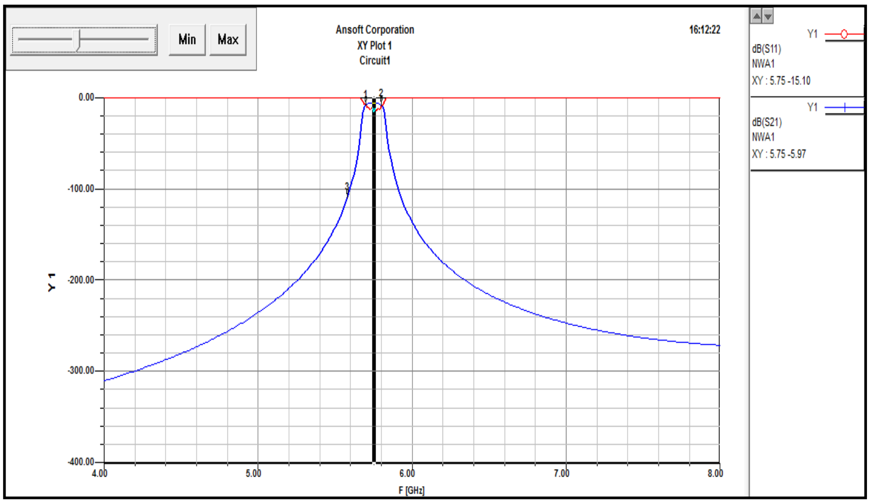

Fig. 10: Optimized frequency response of band pass filter using TLY-5A

Figure 11 is the frequency response for FR4. The insertion loss is -10.95dB. The return loss of the optimized FR4 yielded a value of -11.41dB and the bandwidth is around 463MHz. The Optimization of FR4 seemed to have improved the filter in terms of insertion loss and return loss whereas the bandwidth has increased if compared to the filter before any optimization was done.

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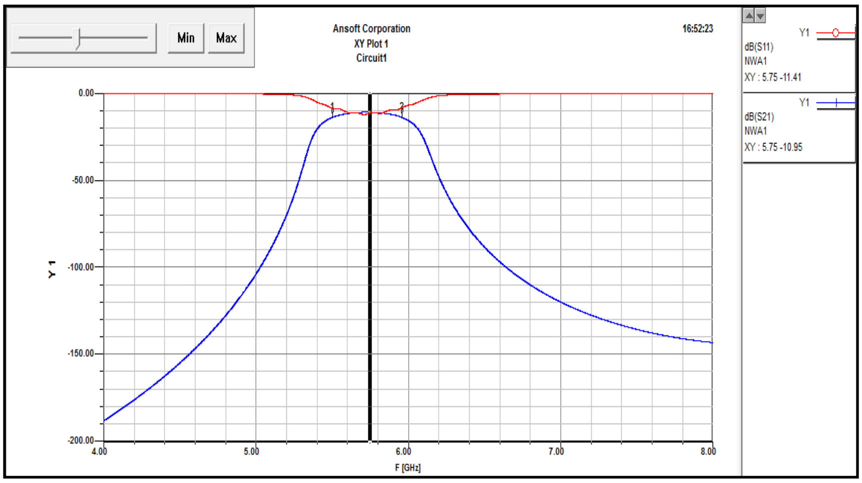

Fig. 11: Optimized frequency response of band pass filter using FR4

Table 10 compares the simulated results of both TLY-5A and FR4 with the theoretical values. On comparison, TLY-5A filter achieves the expected results whereas FR4 is better in terms of insertion loss and return loss after optimization but the bandwidth of the FR4 has increased by 363MHz.

Table 10: Comparison of target and optimized simulated result for conventional 9th order band pass filter using substrate TLY-5A

Design Specifications	Expected Results	TLY-5A Simulated Results	FR4 Simulated Results
Cut Off Frequency	5.75 GHz	5.75 GHz	5.75 GHz
Insertion Loss, S_{21}	< -10 dB	-5.97 dB	-10.95 dB
Return Loss, S_{11}	>-10 dB	-15.10dB	-11.41 dB
Bandwidth	100 MHz	100 MHz	463 MHz

Table 11 shows the effects of varying the width W, spacing S and physical length P of each coupled line. The effects were obtained from parameter study of each parameter. Parameter under study is varied while the others are kept constant.

Table 11: Effect of varying the parameters W, S and P

Specifications	**Altering W**		**Altering S**		**Altering P**	
Status	Increase	Decrease	Increase	Decrease	Increase	Decrease
Center Frequency	No effect	No effect	No effect	No effect	Shifts to the left	Shifts to the right
S_{21}	Decrease	Increase	Increase	Decrease	Decrease	Increase
S_{11}	Decrease	Decrease	Increase	Decrease	Decrease	Decrease
Bandwidth	No effect	No effect	Decrease	Increase	No effect	No effect

B. Λ-type Chebyshev 9th Order Bandpass Filter

The proposed Λ type filter minimizes the size of the structure mainly by changing the shape of the parallel coupled lines. Fig. 12 and 13 are the design of the proposed Λ-type Chebyshev 9th order bandpass filter using TLY-5A and FR4 respectively. The Λ type filter exhibits an area reduction of 51 % compared to the conventional filter.

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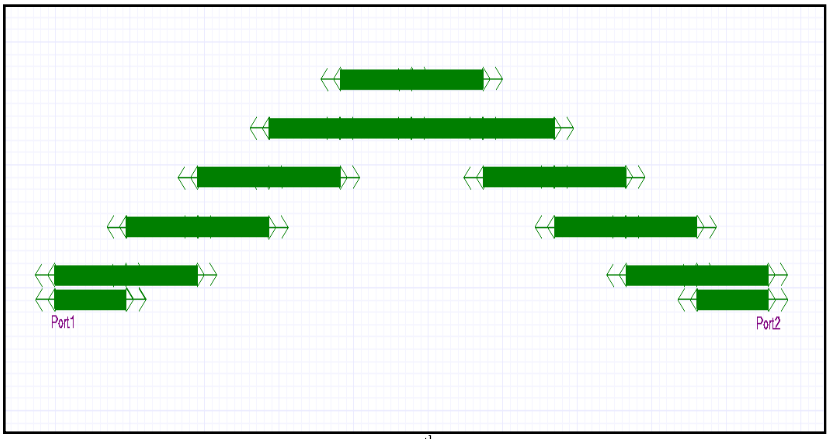

Fig. 12: Layout of Λ-type Chebyshev 9th order band pass filter uing TLY-5A

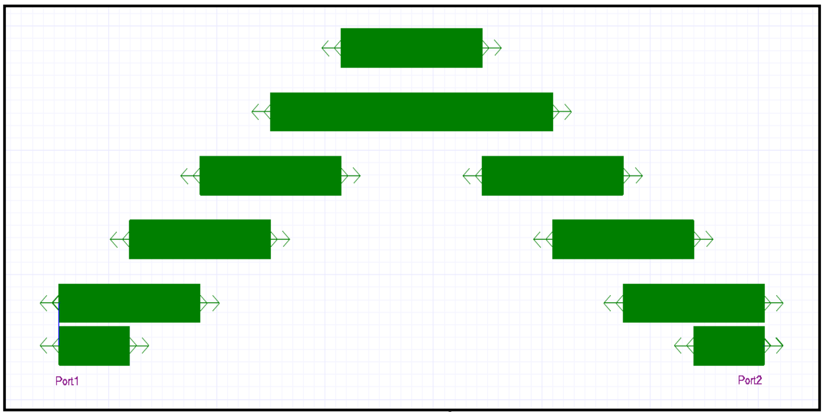

Fig. 13: Layout of Λ-type Chebyshev 9th order band pass filter usingFR4

Fig. 14 shows the frequency response of Λ-type Chebyshev 9th order bandpass filter for TLY-5A, the insertion loss for the Λ-type bandpass filter design on TLY-5A is -5.97dB and the return loss is -15.10dB at a cut-off frequency 5.75GHz. The bandwidth measured in the range of frequencies between 5.701GHz and 5.803GHz is 102MHz.

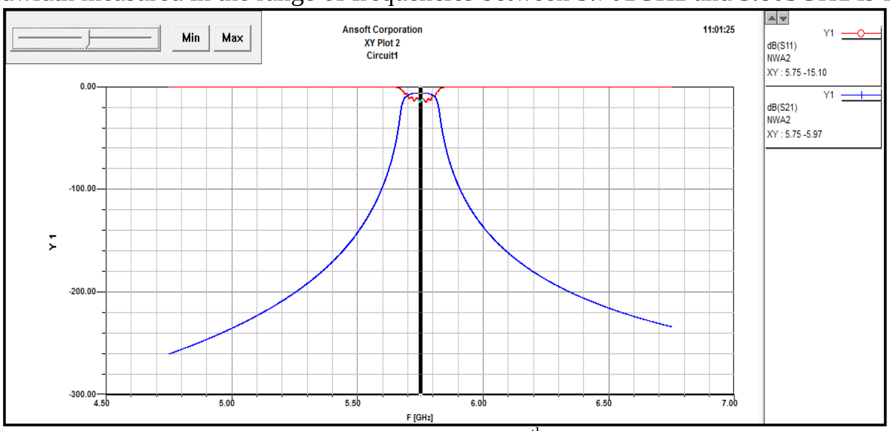

Fig. 14: Frequency response of Λ-type Chebyshev 9th order band pass filter for TLY-5A

Fig. 15 is the frequency response of Λ-type Chebyshev 9th order bandpass filter for FR4. The insertion loss (S_{21}) of Λ-type bandpass filter is -10.95dB and the return loss (S_{11}) is -11.45dB at cut-off frequency 5.75GHz. The bandwidth measured is the range of frequency between 5.499GHz and 5.962GHz is 463MHz.

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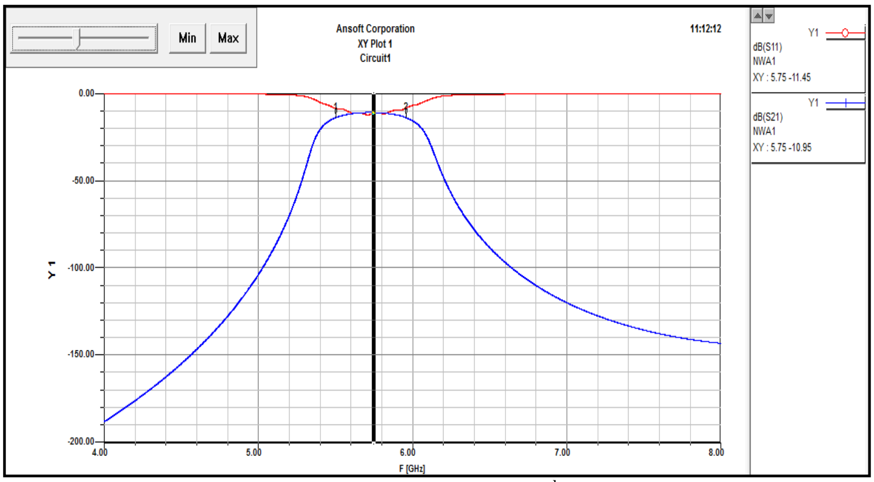

Fig. 15: Frequency response of Λ-type Chebyshev 9th order band pass filter for FR4

Table 12 is the comparison of Λ-type Chebyshev 9th order bandpass filter simulation results. The Λ-type 9th order bandpass filter design on TLY-5A substrate achieves the expectation values whereas for FR4, the bandwidth does not meet the specification. However, the bandwidth of Λ-type bandpass filter designed on FR4 is getting narrower than that of the conventional bandpass filter designed on FR4.

Table 12: Comparison of Λ-type Chebyshev 9th order band pass filter results

Parameters	**Design Specifications**	**Simulated Results**	
		TLY-5A	**FR4**
Cut Off Frequency	5.75 GHz	5.75 GHz	5.75 GHz
Insertion Loss, S_{21}	< -10 dB	-5.97dB	-10.95dB
Return Loss, S_{11}	>-10 dB	-15.10dB	-11.45dB
Bandwidth	100 MHz	100 MHz	463MHz

Table 13 compares the parameters of for conventional and Λ-type Chebyshev 9th order bandpass filter designed using TLY-5A andFR4. The results of the filter using TLY-5A are approximately the same. On the other hand, the frequency response for Λ-type designed on substrate FR4 is better compared to the conventional as the bandwidth is narrower than the conventional. However the insertion loss decreased by 1.28dB.

Table: 13: Comparison between conventional and Λ-type bandpass filter

Parameters	TLY-5A		FR4	
	Conventional	Λ - Type	Conventional	Λ - Type
Frequency GHz	5.75	5.75	5.75	5.75
Insertion Loss, S_{21} dB	-5.97	-5.97	-10.9	-10.95
Return Loss, S_{11} dB	-15.10	-15.10	-11.41	-11.45
Bandwidth MHz	100	102	463	463

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VI. CONCLUSION

The paper has presented a design structure for the reduction of size of the 9th order Chebyshev bandpass filter. The size of the bandpass filter is reduced by 51 % compared to conventional filter. The results also indicate that the filter designed with TLY-5A exhibits a comparable response in comparison with conventional filter. Optimization can be still carried over the improvement of insertion and return loss.

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