

## DESIGN OF A MICROSTRIP MAXIMALLY FLAT 7TH ORDER LOWPASS FILTER USING ADS SIMULATION

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### Abstract

This work presents the design and analysis of a 7<sup>th</sup> order microstrip maximally flat low pass filter using insertion loss method in X-band range. The cutoff frequency at 10 GHz. An attenuation of more than 60 dB is obtained. The low pass filter was designed and simulated using Advanced Design System (ADS) software. The filter is implemented on Alumni substrate having a dielectric loss of 9.6 and substrate height of 1.6 mm. In addition, an optimization process for the stub lengths and widths is performed based on desired filter specifications. Due to coupling effect between adjacent stubs, the desired filter specifications become difficult to be achieved and the optimization process can solve for that by defining thresholds that match the desired filter specifications.

Keywords: Attenuation, Distributed elements, Insertion loss, Lumped elements, Maximally flat, Microstrip, Stubs.

## 1. Introduction

Low pass filters are found as major blocks in communication systems. Low pass filters are used to eliminate noise of mixers, low noise amplifiers, voltage-controlled oscillators and power amplifiers. Filter design realization using lumped elements becomes very difficult above 500 MHz [1]. The wavelength becomes comparable to the physical element dimensions and thus resulting in system performance degradation. Microstrip transmission lines are used to convey microwave frequencies and they are easily fabricated using printed circuit board technology. In addition, microstrip lines are efficient regards to cost and compact in size.

Ludwig and Bretchko [2] and Ninikrishna and Sreelakshmi [3] presented a practical filter realization using distributed elements. As the filter order is higher, sharper frequency response will be obtained. Ninikrishna and Sreelakshmi [3] deigned and analysed a maximally flat low pass filter with 7<sup>th</sup> order at a cutoff frequency of 10 GHz and a sharp rejection of more than 60 dB in X-band range was obtained.

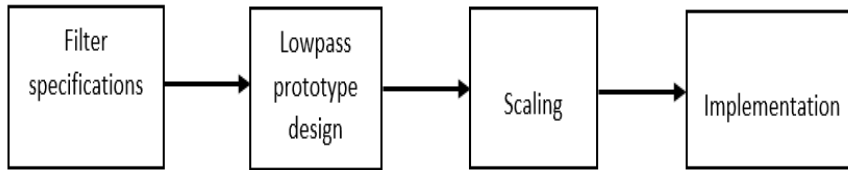
Rajasekaran et al. [4] designed an X-band stepped impedance low pass filter to work at 10 GHz at the centre frequency and with an attenuation of 60 dB. Naghar et al. [5] designed a band pass filter for 5 GHz Unlicensed WiMAX using parallel-coupled microstrip. The structure was simulated in both ADS and CST. Both simulators show a good agreement. Tuneable lowpass and bandpass filter was designed by Sharif et al. [6] using shunt stub resonators. The filter was implemented on Rogers RT/Duroid 5880 substrate having a dielectric loss of 2.2 and substrate height of 0.8 mm. The overall frequency band was adjusted using a varactor diode. The filter has a low range of insertion loss from 0.29 to 1.14 dB. While Madhumitha et al. [7] designed a bandpass filter to operate on GSM band with an insertion loss of more than 1.8 dB.

Usually for lower cost, microstrip lines are printed on FR-4 substrate. If FR-4 substrate is used, then the dielectric losses become high at microwave frequencies. In this work a 7<sup>th</sup> order microstrip maximally flat low pass filter is implemented on Alumina substrate to compensate for the effect of dielectric losses [4]. The design of the prototype filter is performed in Advanced Design System and the obtained results are analysed.

Due to coupling effect between stubs in the filter design using microstrip line technology, the desired filter specifications are not being matched. To compensate for the coupling effect between adjacent stubs, optimization process to adjust the stub lengths and widths is performed based on predefined thresholds in ADS that can match the desired filter specifications. After optimization, a passband bandwidth of 10 GHz is obtained. The return loss and the insertion loss are -4.77 dB and -2.0 dB at 10 GHz respectively which is a little bit close to the -3 dB and a very high attenuation of less than -40 dB is obtained at 11 GHz.

## 2. Filter Design and Mathematical Calculation

Filter design using the method of insertion loss includes the design of a passive element low pass filter with a normalized cut off frequency of 1 rad/s and a source impedance of 1 Ohm, then impedance and frequency are scaled to get the desired source and load impedances as well as the desired frequency specifications. For the filter design to be implemented at microwave frequencies, the passive element components have to be replaced with distributed elements. The steps of filter design are summarized in Fig. 1.



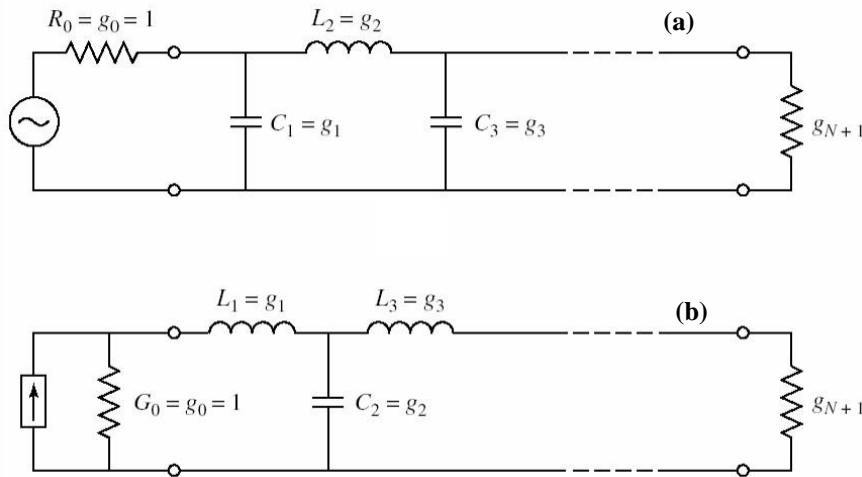
**Fig. 1. The filter design steps using insertion loss method.**

In the method of insertion loss, the filter response is defined as its power loss ratio,  $P_{LR}$ , [8]:

$$P_{LR} = \frac{P_{inc}}{P_L} = \frac{1}{1-|\rho|^2} \tag{1}$$

where  $P_{inc}$  is the total incident power,  $P_L$  is the power delivered to the load, and  $\rho$  is the reflection coefficient.

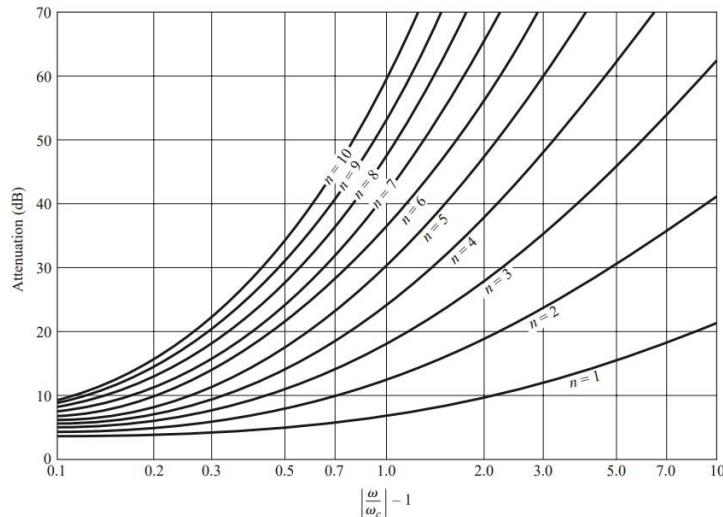
In maximally flat low pass filter design, two different prototypes of ladder-type circuits can be used, Figs. 2. The prototype in Fig. 2(a) is beginning with a shunt lumped element, while in Fig. 2(b), its beginning with a series element. The inductance and capacitance values in Figs. 2 are normalized values where the source impedance is 1 Ohm and the cutoff frequency is  $\omega_c = 1 \text{ rad/s}$ .  $g_0$  and  $g_{N+1}$  represent the normalized source and load impedances respectively, where  $N$  is the filter order. Table 1 shows the inductance and capacitance values of a maximally flat low pass filter for  $N = 1$  to 9. The attenuation for various  $N$ , versus normalized frequency are shown in Fig. 3 for a maximally flat low pass filter.



**Fig. 2. Ladder circuits for low pass filter prototypes. (a) Ladder circuit starts with an element in parallel. (b) Ladder circuit starts with an element in series.**

**Table 1. Element values for maximally flat low pass filter prototype ( $g_0 = 1, \omega_c = 1, N = 1$  to 9).**

$N$	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$	$g_6$	$g_7$	$g_8$	$g_9$	$g_{10}$
1	2.0000	1.0000								
2	1.4140	1.4140	1.0000							
3	1.0000	2.0000	1.0000	1.0000						
4	0.7654	1.8478	1.8478	0.7654	1.0000					
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000				
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000			
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000		
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000	
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0000



**Fig. 3. The attenuation versus normalized frequency for a maximally flat low pass filter (consider that  $n$  is the order of the filter) [8].**

### 3. Impedance and Frequency Scaling

In the prototype design the source and load impedances are unity. To obtain impedance scaled quantities, each impedance in the prototype should be multiplied by a source impedance  $Z_o$ . Regards to the frequency scaling, to change the cutoff frequency of a low pass prototype from unity to  $\omega_c$  then the frequency dependence of the filter should be scaled by the factor  $1/\omega_c$ .

After impedance and frequency scaling, the inductance and capacitance values will be given by

$$L'_k = \frac{Z_o L_k}{\omega_c}, \text{ and}$$

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

where,  $Z_o$  is the source impedance,  $\omega_c$  is the cutoff frequency,  $L_k$  is the inductance value, and  $C_k$  is the capacitance value.

### 4. Filter Realization using Distributed Elements

At microwave frequencies, filter design based on lumped elements becomes insufficient for two main reasons: the lumped elements are with limited range of values and the distance between lumped elements is not negligible at microwave frequencies. By using Richard’s transformation, an inductor is replaced by a short-circuited stub, while a capacitor is replaced by an open-circuited stub. The reactance of an inductor  $X_L$  and the susceptance of a capacitor  $B_C$  can be written as

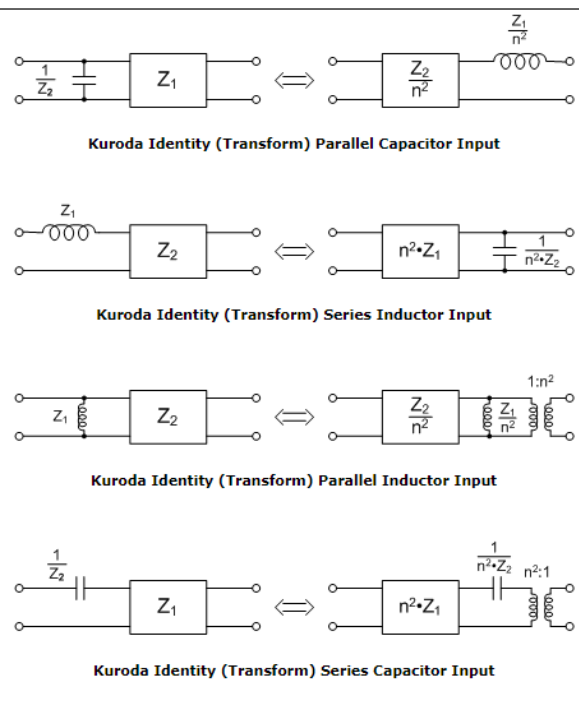
$$jX_L = j\Omega L = jL \tan \beta l, \text{ and}$$

$$jB_L = j\Omega C = jC \tan \beta l \tag{3}$$

where,  $X_L$  is the inductor reactance,  $B_C$  is the capacitor susceptance  $\Omega = \tan \beta l$ , and  $\beta l$  is the electrical length of the microstrip line. To get cutoff frequency at unity for a lowpass filter prototype, a stub length of  $l = \lambda/8$  is required. Where  $\lambda$  is the wavelength of the line at the cutoff frequency,  $\omega_c$ .

To achieve more practical microwave filter realization, the Kuroda identities in Table 2 are used. Unit elements of length  $\lambda/8$  are inserted based on Kuroda identities. Transforming series stubs into shunt stubs and vice versa becomes possible by Kuroda identities.

**Table 2. The Kuroda identities ( $n^2 = 1 + Z_2/Z_1$ ).**



## 5. Filter Specification and Design Methodology

In this work a maximally flat lowpass filter will be designed, the filter specifications are summarized in Table 3. The order of the filter is chosen to be 7,  $N = 7$ , then the filter rolls off at a sharper rate after the bandwidth and then rapid attenuation achieved. The lowpass filter element values, Table 1

$$\begin{aligned}
 g_0 &= 1, \\
 g_1 &= g_7 = 0.445, \\
 g_2 &= g_6 = 1.247, \\
 g_3 &= g_5 = 1.8019, \text{ and} \\
 g_4 &= 2
 \end{aligned} \tag{4}$$

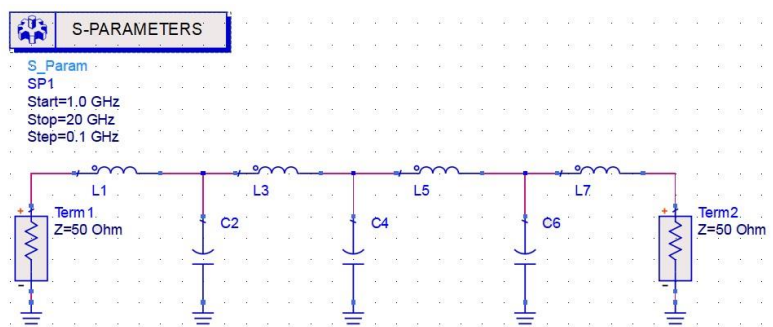
Ladder circuit beginning with a series element of Fig. 2(b) is chosen. Using frequency and impedance scaling in eq.2, the corresponding  $L$  and  $C$  values

$$\begin{aligned}
 L_1 &= L_7 = 0.354 \text{ nH}, \\
 C_2 &= C_6 = 0.397 \text{ pF}, \\
 L_3 &= L_5 = 1.435 \text{ nH}, \text{ and} \\
 C_4 &= 0.637 \text{ pF}
 \end{aligned} \tag{5}$$

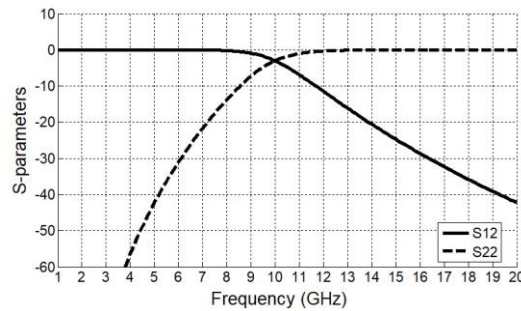
The 7<sup>th</sup> order maximally flat lowpass filter with the specifications of Table 3 and lumped element values calculated in Eq. (5) is designed in ADS as shown in Fig. 4. The simulated S-parameters are shown in Fig. 5. For a 7<sup>th</sup> order maximally flat lowpass filter, the stop band attenuation is around -40 dB if  $\left| \frac{\omega}{\omega_c} \right| - 1$  is taken to be unity. As could be seen from Fig. 5, an attenuation of -40 dB and a cut off frequency of 10 GHz are obtained.

**Table 3. Filter specifications.**

Centre frequency	10 GHz
Stop band attenuation	-42 dB
Substrate height	1.6 mm
Dielectric constant (Alumina)	9.6
Source and load impedances	50 Ohm

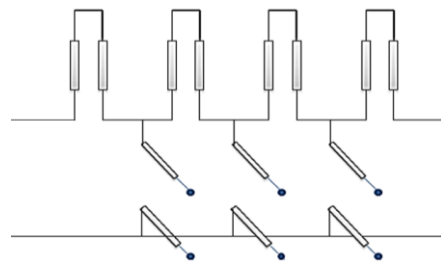


**Fig. 4. Schematic diagram of a 7<sup>th</sup> order maximally flat lowpass filter in ADS.**



**Fig. 5. The simulated S-parameters (ADS Schematic).**

For practical filter design, it is required to convert the passive elements to distributed elements, and to do that Richard’s transformation and Kuroda’s identities have to be used. Based on Richard’s transformation the inductors and capacitors in the filter design shown in Fig. 4 are replaced by short circuited and open circuited stubs respectively as shown in Fig. 6. Then it is required to separate the transmission line components spatially.

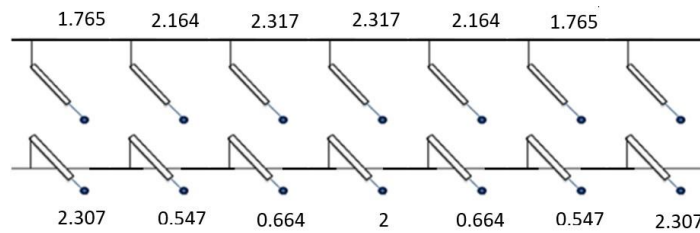


**Fig. 6. Converted from lumped elements to distributed elements using Richard’s transformation.**

To do that, inserting unit elements is required. In parallel to inserting unit elements, Kuroda’s identities summarized in Table 2 are used to convert the series stubs into shunt stubs for more suitable realization. Final realization of the filter is shown in Fig. 7 with open circuited shunt stubs separated by unit elements of transmission lines. The impedances in Fig. 7 are normalized impedances and they can be denormalized by scaling the elements to 50  $\Omega$  impedance. Table 4 summarizes the normalized and denormalized impedance values of the unit elements and shunt stubs and the corresponding transmission line lengths and widths. For lower impedance values the stub width becomes wider. The 7<sup>th</sup> order maximally flat lowpass filter is modelled using microstrip lines based on the corresponding lengths and widths calculated in Table 4.

The schematic diagram of the lowpass filter using microstrip lines is modelled in ADS as shown in Fig. 8. The corresponding S-parameters are simulated in ADS and shown in Figs. 9(a) and (b). At 10 GHz the return loss and the insertion loss

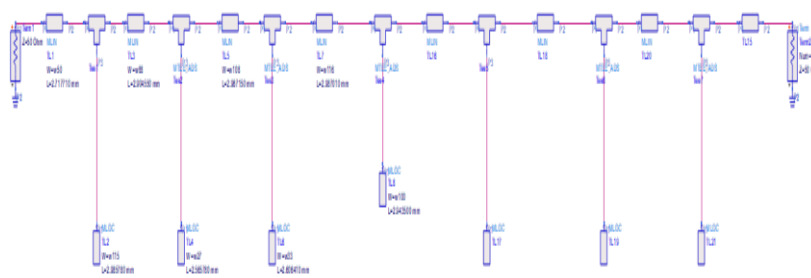
are -0.06 dB and -39.13 dB respectively. Compared to the S-parameters in Fig. 5 (lumped elements realization), distortion due to coupling effect between adjacent stubs in microstrip line realization is clear to see above 6 GHz. To compensate for coupling effect and obtain the desired filter specifications, an optimization process in ADS is performed by predefining certain threshold values that match the desired specifications. The optimized stub lengths and widths that satisfy the desired filter specifications are summarized in Table 5. Obtained results after optimization process are compared with existing researches in Table 6. The corresponding S-parameters are shown in Figs. 10(a) and 10(b). After optimization, the return loss and the insertion loss are -4.77 dB and -2.0 dB at 10 GHz respectively which is a little bit close to the -3 dB and an attenuation of less than -60 dB is obtained. The layout for the schematic diagram of the lowpass filter in Fig. 8 is shown in Fig. 11. Wider stub widths are corresponding to lower impedance values. The characteristic impedance value of the microstrip line is inversely proportional to the line width.



**Fig. 7. Realization of the 7<sup>th</sup> order maximally flat low pass filter using Kuroda's identities.**

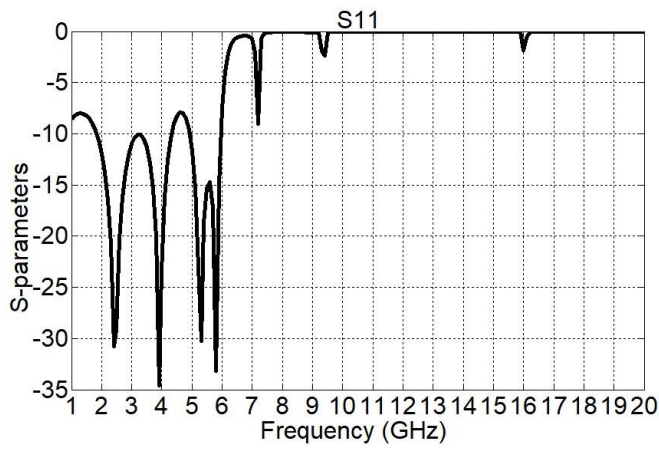
**Table 4. The normalized and denormalized impedance values and corresponding transmission line lengths and widths.**

Normalized impedances	Denormalized impedances( $\Omega$ )	Length (mm)	Width (mm)
2.307	115.35	2.986	0.165
1.765	88.25	2.905	0.453
0.547	27.35	2.566	5.094
2.164	108.2	2.967	0.216
0.664	33.2	2.606	3.824
2.317	115.85	2.987	0.162
2	100	2.944	0.293

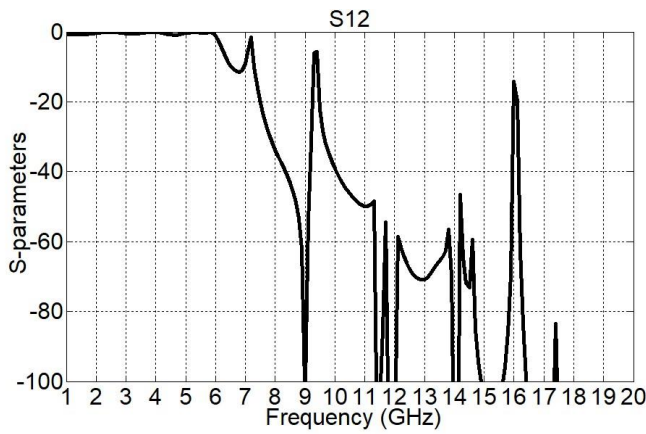


**Fig. 8. The schematic diagram of the 7<sup>th</sup> order maximally flat low pass filter using microstrip lines in ADS.**





(a)



(b)

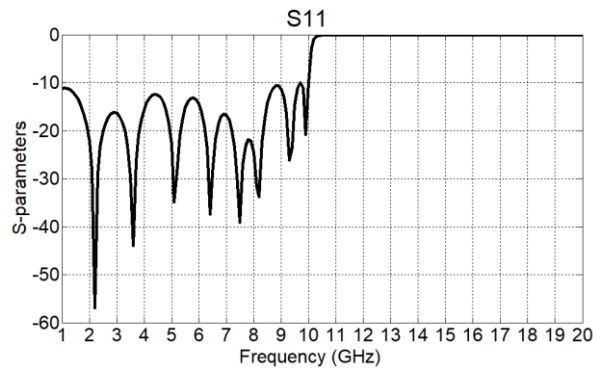
**Fig. 9. The simulated S-parameters: (a) Return loss, and (b) Insertion loss for the filter realization in Fig. 8.**

**Table 5. The optimized and nonoptimized values of the stub lengths and widths.**

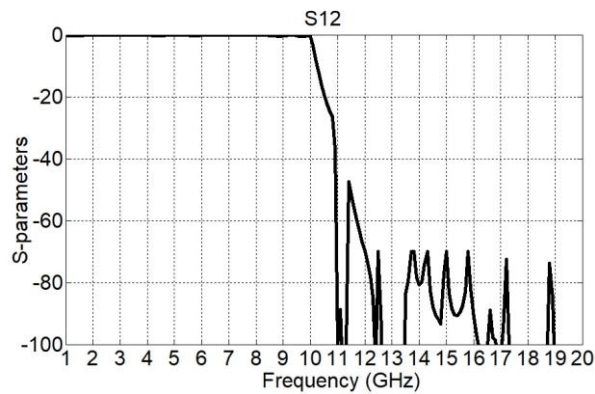
Nonoptimized values		Optimized values	
Length (mm)	Width (mm)	Length (mm)	Width (mm)
2.986	0.165	2.28339	0.185371
2.905	0.453	2.29614	0.664408
2.566	5.094	1.26133	2.77579
2.967	0.216	2.86715	0.654418
2.606	3.824	1.55564	4.42775
2.987	0.162	3.37357	0.741735
2.944	0.293	1.45529	0.230201

**Table 6. Obtained results in comparison with existing researches.**

Ref.	Response type	Passband bandwidth	attenuation	Substrate	Filter size mm <sup>2</sup>
[1]	Defected ground structure	3 GHz	-50 dB	RT Duroid 588 ( $h = 0.787$ mm, $\epsilon_r = 2.2$ )	----
[4]	Butterworth	8.5 GHz	-40 dB	Alumina ( $h = 0.63$ mm, $\epsilon_r = 9.6$ )	7.34×3.8
[6]	Butterworth	0.93 GHz	-30 dB	RT Duroid 588 ( $h = 0.8$ m, $\epsilon_r = 2.2$ )	108.4×47.5
This work	Butterworth	10 GHz	<-60 dB	Alumina ( $h = 1.6$ mm, $\epsilon_r = 9.6$ )	9×3.45

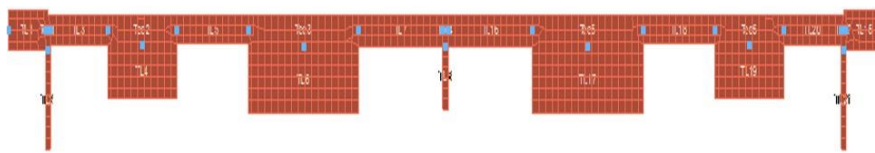


**(a) Return loss**



**(b) Insertion loss for the filter realization**

**Fig. 10. The simulated S-parameters in Fig. 8. (optimized values).**



**Fig. 11. The 7<sup>th</sup> order maximally flat lowpass filter layout in ADS (optimized values are considered).**

## 6. Conclusion

In this work, a seventh order maximally flat low pass filter is designed using the Advanced Design System simulation tool ADS. The lowpass filter is designed in both lumped elements and distributed elements. The lumped element values are calculated based on insertion loss method. The S-parameters obtained from the lumped elements filter design strongly meet the filter specification determined in Table 3. For filter design realization, the passive elements are required to be converted to distributed elements. Richard's transformation and Kuroda's identities are used for such conversion. The final realization of the seventh order low pass filter consists of shunt stubs separated by unit elements. The simulated S-parameters are presented for both cases: with optimized and nonoptimized values of stub lengths and widths. Optimization process is required to compensate for the coupling effect between adjacent stubs in microstrip line realization and satisfy the desired filter specifications. After optimization, a return loss of -4.77 dB is obtained at 10 GHz and an insertion loss of -2.0 dB. attenuation of more than 60 dB is obtained.

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