

# Design and Optimization of high Frequency Lowpass Filter on RO4003C Microstrip Using maximally-Flat (Butterworth) Technique

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**Abstract**—In this paper, the design and optimization of Lowpass Filter Using Maximally-Flat (Butterworth) Technique is proposed. The realization of seven order Lowpass filter on Microstrip transmission lines was carried out. MATLAB and AWR software were used for the implementation.

**Keywords:** - Lowpass Filter, RO4003C microstrip, MSTEPX\$, Attenuation, Lumped elements, frequency, scattering parameters

## INTRODUCTION

Filters have important roles in communication/radar systems, and their usage is unavoidable when rejection of an unwanted frequency range is required. Filtering is also a major approach in electromagnetic compatibility (EMC) engineering, for the cancellation of noise and interference. Functionally, filters can be grouped into four categories: low-pass filters (LPF), high-pass filters (HPF), bandpass filters (BPF), and band-stop filters (BSF). There are various sets of analytical functions that satisfy given filter specifications, but Butterworth, Chebyshev, Cauer, and Bessel functions, with their pros and cons, are the functions widely used in RF/microwave filter design. For example, Butterworth filters are maximally flat in the pass band, but their out-of-band attenuation slopes are not good. Chebyshev filters have sharper attenuation slopes (as compared to Butterworth filters), but the payoff is the ripple inside the pass band. Elliptic filters have the sharpest out-of band attenuation, but they have undesired ripples both in and out of the pass band.

Today, most microwave filter designs are done with computer-aided design (CAD) packages, such as Advancing the Wireless Revolution, Ansoft Designer, etc based on the insertion loss method. In this work, the Butterworth lowpass filter design is taken into consideration.

The aim of this work is to design and optimize lowpass filter using maximally-flat (Butterworth) Technique with the following specifications:

Source Impedance,  $Z_0=50\Omega$ , Load Impedance,  $Z_L=50\Omega$ . The dielectric substrate to be used in the microstrip will be RO4003C with the height of 1.52 mm. The typical parameters of this dielectric are given as  $\epsilon_r = 3.38$ ,  $\tan \delta = 0.0027$ , and metal cladding of  $35\mu\text{m}$ . The highest practical characteristic impedance to be implemented on the microstrip is  $130\Omega$ , and the lowest is  $18\Omega$ . The filter should have a cut off frequency (where attenuation is 3 dB) of 2.4 GHz and give minimum 30 dB attenuation at 4.08 GHz.

The objectives are:

- (i) Calculations and MATLAB simulations of the filter with lumped elements (Approximate solution)
- (ii) Calculations and MATLAB simulations of the filter with microstrip transmission lines (Almost exact solution)
- (iii) Implementation of the filter design on AWR Microwave design and optimization/tuning (Engineering solution)
- (iv) Implementation of the filter design on AWR Microwave design by considering discontinuities and optimization/tuning (Practical solution).

## DESIGN OF THE FILTER

### (A) First phase (Lumped element approach)

A procedure, called the *insertion loss method*, is used here which uses network synthesis techniques to design filter with a completely specified frequency response. The design is simplified with low-pass filter prototypes that are normalized in terms of impedance and frequency. The normalized element values are obtained for maximally flat filter design from table 2.1 below.

From the given specification on the insertion loss, the filter order can be obtained as

$|\omega/\omega_c| - 1 = |(2\pi \times 4.08/2\pi \times 2.4)| - 1 = 0.7$ ; from fig. 2.1 below, it is found that,  $N = 7$  will be sufficient. Then table 1 gives the prototype elements as:  $g_0=1.0000, g_1=0.4450, g_2=1.2470, g_3=1.8019, g_4=2.0000, g_5=1.8019, g_6=1.2470, g_7=0.4450, g_8=1.0000$ .

The un-normalized values can be obtained from the normalized values using the following formulae:

$$L'_k = L_k R_o / \omega_c \quad (1)$$

$$C'_k = C_k / R_o \omega_c \quad (2)$$

Table 2.1: Element values for maximally Flat Low-pass Filter Prototypes ( $g_0=1, \omega_c=1, N=1$  to 10)

N	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$	$g_6$	$g_7$	$g_8$	$g_9$	$g_{10}$	$g_{11}$
1	2.0000	1.0000									
2	1.4142	1.4142	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	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	1.0000

Source: Reprinted from G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures* (Dedham, Mass.: Artech House, 1980) with permission.

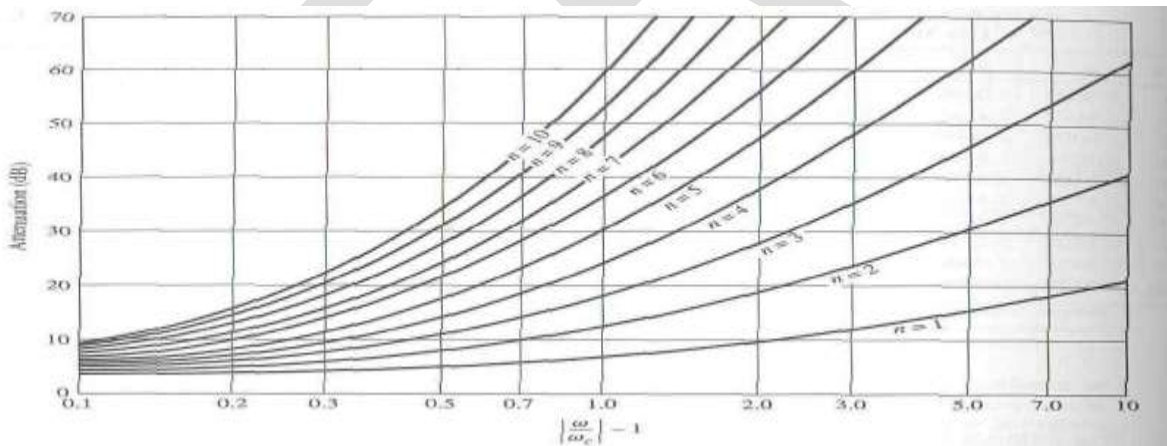


Fig. 2.1: Attenuation versus normalized frequency for maximally flat filter prototype

MATLAB was used to obtain the following results from equation (1) and (2) above.

$$C'_1 = 0.5902\text{pF},$$

$$L'_2 = 4.1347\text{nH},$$

$$C'_3 = 2.3898\text{pF},$$

$$L'_4 = 6.6315\text{nH},$$

$$C'_5 = 2.3898\text{pF},$$

$$L'_6 = 4.1347\text{nH},$$

$$C'_7 = 0.5902\text{pF},$$

The filter circuit is drawn using AWR software and is shown in fig. 2.2 below

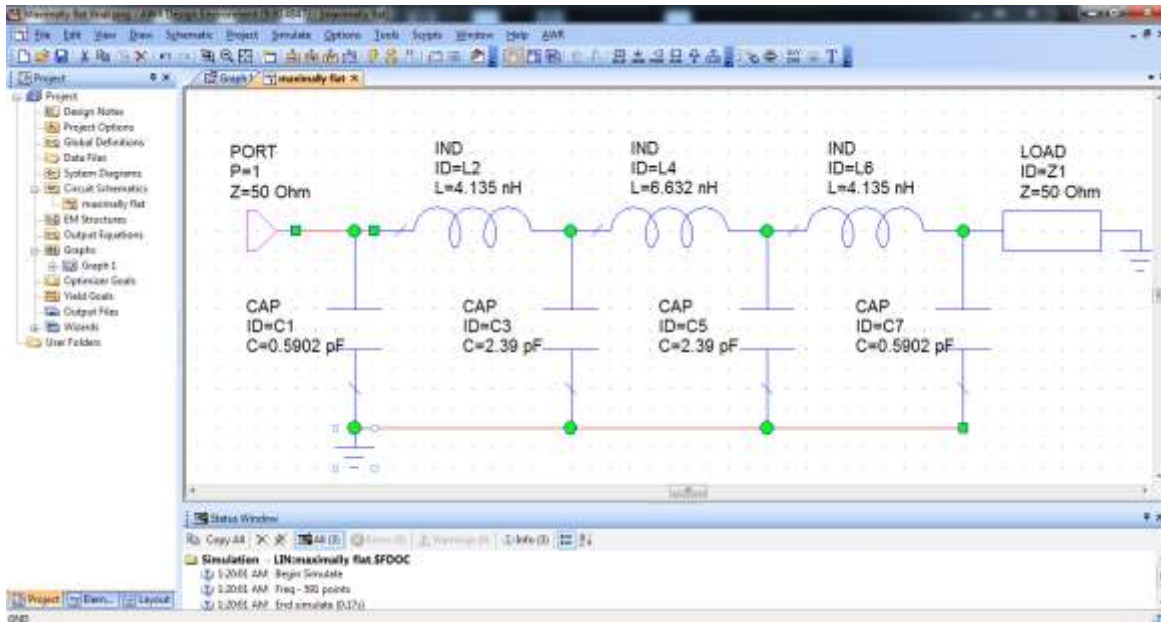


Fig. 2.2, Low pass, maximally flat with N=7, filter circuit

MATLAB is used to obtain the scattering parameters graphs (S11 vs. frequency graph) and (S21 vs. frequency graph) shown in figure 2.3 below.

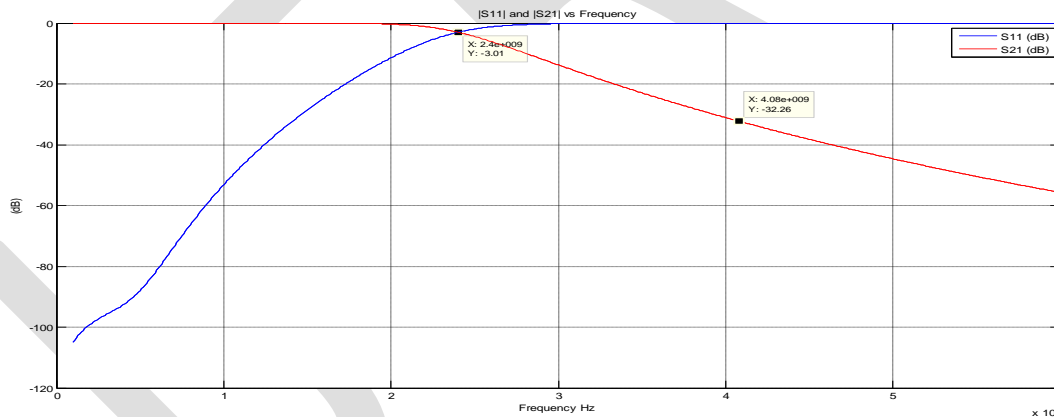


Fig. 2.3, the graph of S11 and S21 verses Frequency

**Comment:**

All the frequencies lower than the cut off frequency (2.4 GHz) have attenuation values of below 3 dB and at 4.08 GHz there is 32.26 dB attenuation which is higher than 30 dB.

(B) Second phase (Microstrip transmission line approach)

In this phase, the lengths and characteristic impedances of Microstrip transmission line section will be calculated. The highest practical characteristic Impedance implemented on the Microstrip is 130Ω and the lowest is 18Ω. The effective dielectric permittivity for both 130Ω and 18Ω are calculated using AWR software.  $\epsilon_{\text{eff}} = 2.35$  for 130 Ω, and 3.04 for 18 Ω.

The lengths are calculated using the following formulae for inductors and capacitors respectively,

$$\ell_{\text{ind},k} = L_k V_{p1} / Z_{\text{high}} \quad (3)$$

$$\ell_{\text{cap},k} = C_k V_{p2} Z_{\text{low}} \quad (4)$$

Where  $V_{p1} = \frac{3 \times 10^8}{\sqrt{2.35}} = 195.7 \times 10^6$  m/sec and  $V_{p2} = \frac{3 \times 10^8}{\sqrt{3.04}} = 172.06 \times 10^6$  m/sec are velocities at 130 Ω and at 18 Ω respectively.

Therefore, the lengths of the Microstrip lines are:

$$\ell_{\text{cap},1} = 1.83\text{mm}, \ell_{\text{ind},2} = 6.22\text{mm}, \ell_{\text{cap},1} = 7.4\text{mm}, \ell_{\text{ind},2} = 9.98\text{mm}, \ell_{\text{cap},1} = 7.4\text{mm}, \ell_{\text{ind},2} = 6.22\text{mm}, \ell_{\text{cap},1} = 1.83\text{mm}$$

Using the values of the characteristic impedances and lengths obtained above, MATLAB is used to calculate the overall input impedance and reflection coefficient (S11) using cascade approach and then unitary property of scattering matrix is used to calculate S21.

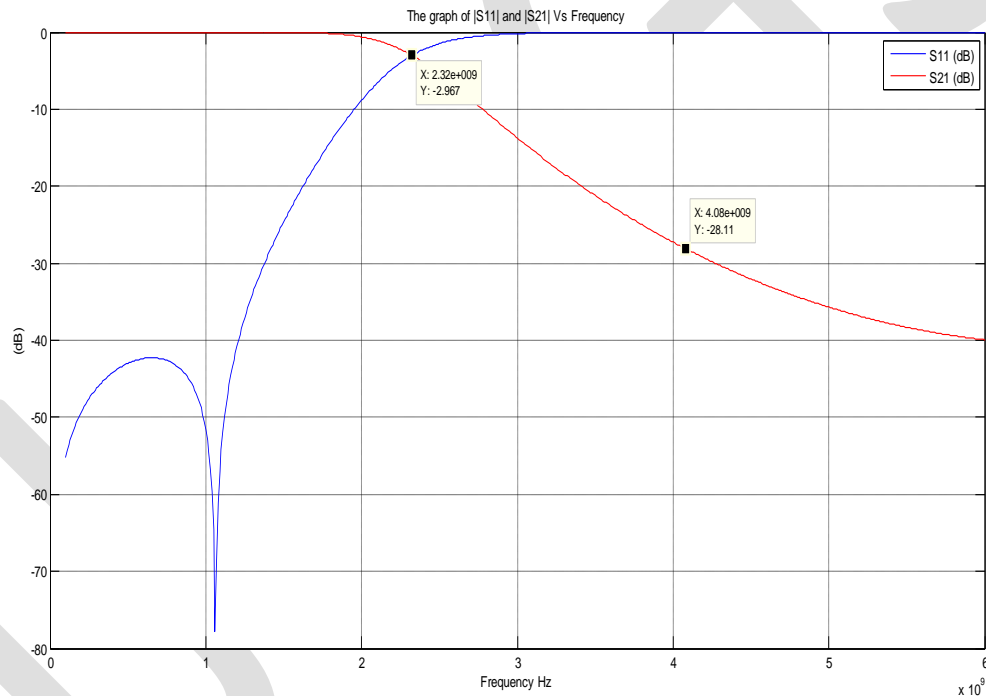


Fig. 2.5, graph of S11 and S21 verses Frequency.

The figure 2.6 below shows the comparison between S21 of the first phase and that of the second phase.

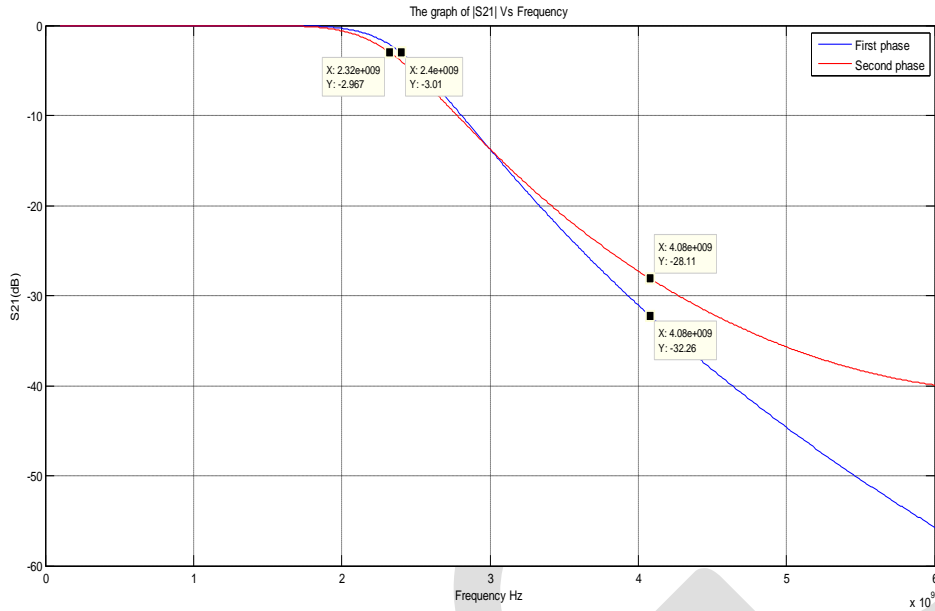


Fig.2.6, the graph of S21 verses Frequency of the first and second phase.

**Comment:**

All frequencies lower than 2.32 GHz which is less than the cut off frequency (2.4 GHz) have attenuation values of below 3 dB and at 4.08 GHz there is 28.11dB attenuation which is less than the specified minimum 30 dB.

Figure 2.6 shows that the first approach (phase) has a better result compare to second phase.

*(C) Third phase (Simulation approach)*

In this phase, the microwave circuit design is implemented and simulated with AWR Microwave Design Environment software. Physical lengths for the lengths of the transmission lines and characteristics impedances calculated in second phase are used. S11 vs. frequency graph and S21 vs. frequency graph on the same figure were drawn with this program and a screen shots were taken as shown in figure2.7 (a) and (b) below.

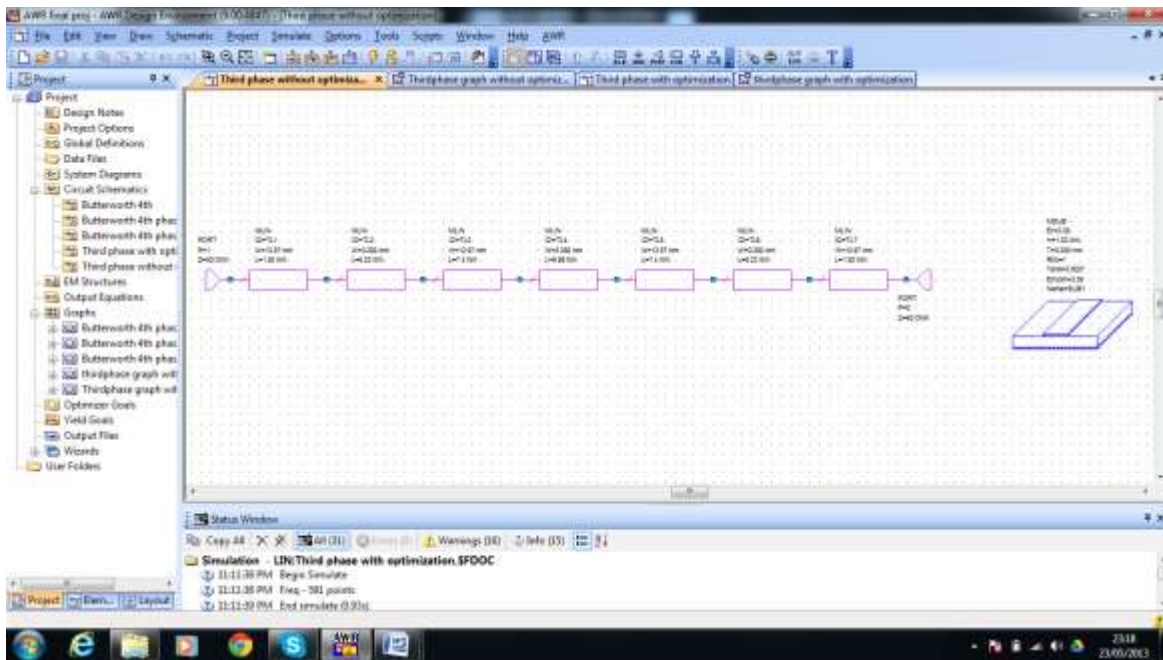


Fig. 2.7(a), AWR simulation of the third phase without optimization

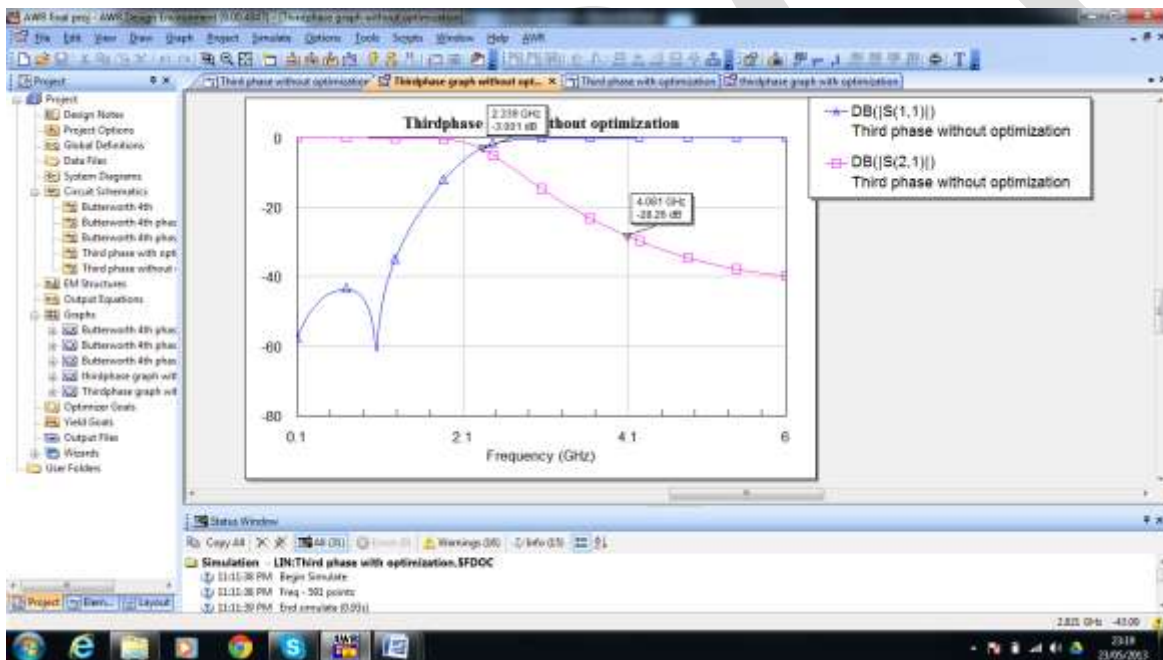


Fig. 2.7(a), S11 and S21 vs. Frequency graph without optimization

**Comment:**

All the frequencies lower than the cut off frequency (2.4 GHz) have attenuation values below 3 dB and at 4.08 GHz there is 28.26 dB attenuation which is less than 30 dB. This result is better than that of second phase since there is no shift in the cut-off frequency unlike in the second phase but still an improvement is needed.



By using the “tune” and “tune tool” of AWR, the performance of the filter was improved as much as possible as shown in fig. 2.8 below. The characteristics impedances were kept constant, while the lengths of sections were tuned. Table 2.2 below shows the original and optimized values of the lengths of the transmission line.

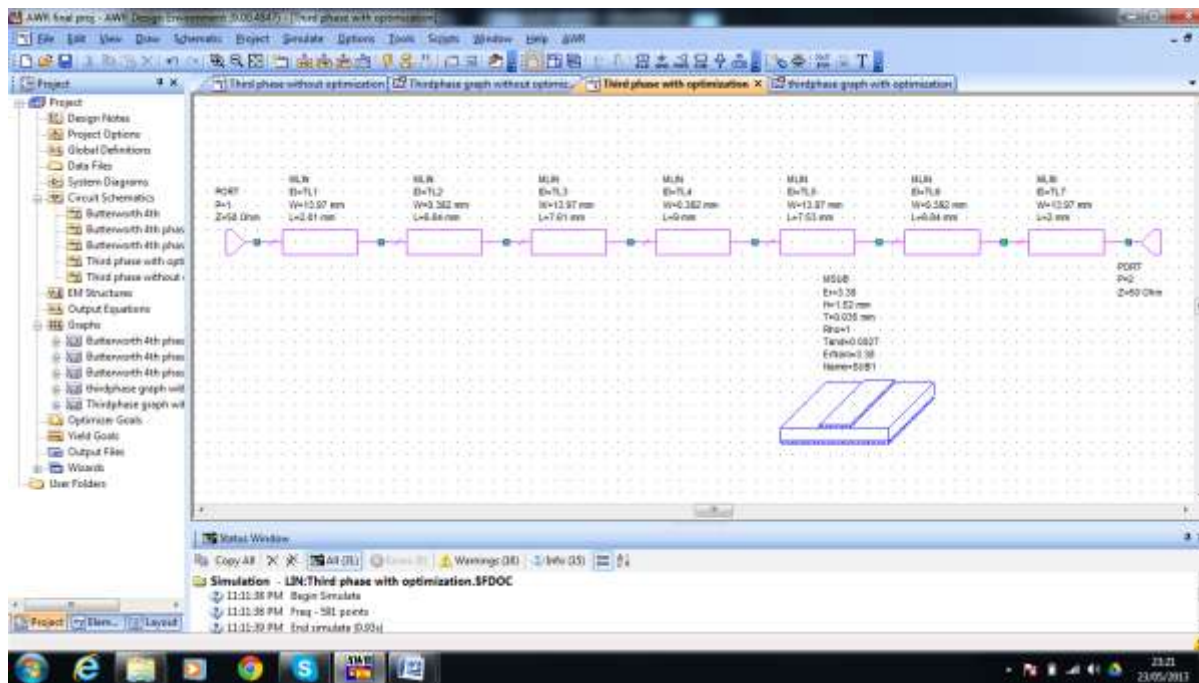


Fig. 2.8(a) simulation of the third phase with optimization

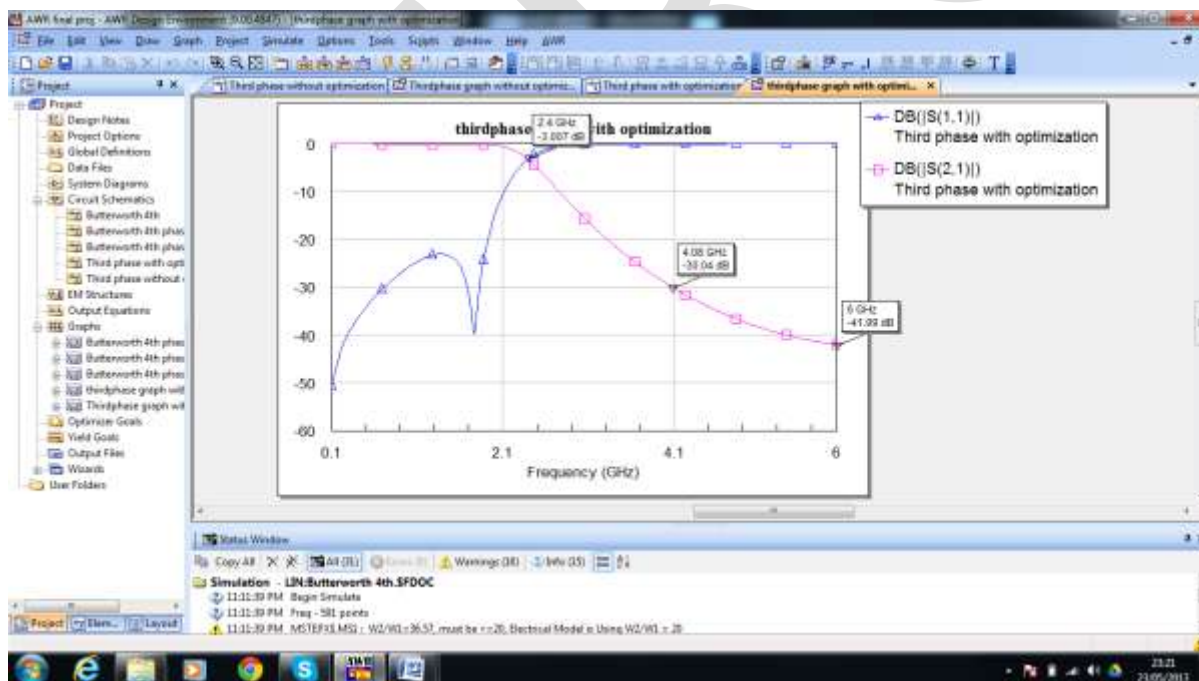


Fig.2.8 (b), S11 and S21 Vs frequency graph with optimization

Table 2.2, original and optimized values of the lengths of the transmission line

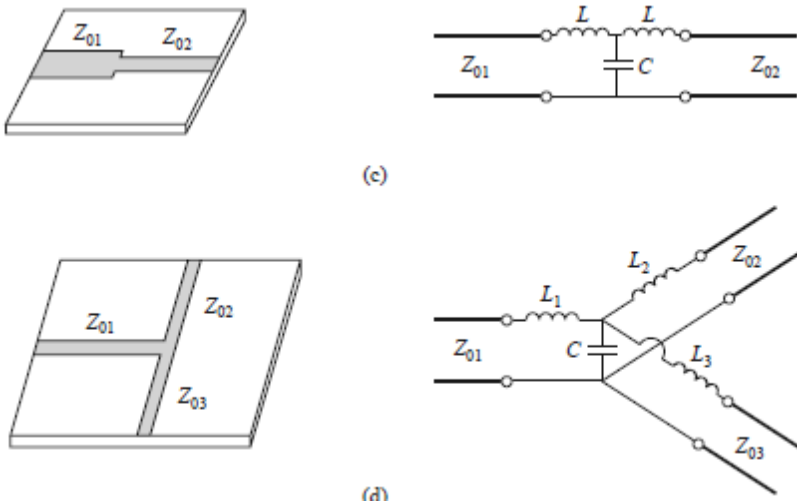
Length of the line	Without optimization	With optimization
$l_{cap,1}$	1.83	2.01
$l_{ind,2}$	6.22	6.84
$l_{cap,3}$	7.40	7.61
$l_{ind,4}$	9.98	9.00
$l_{cap,5}$	7.40	7.53
$l_{ind,6}$	6.22	6.84
$l_{cap,7}$	1.83	2.00

**Comment:**

With optimization (tuning), a better result is obtained for the third phase simulation, here, at 4.08 GHz there is 30.04dB attenuation which is the same as the minimum attenuation specified 30 dB while the cut-off frequency of 2.4 GHz is maintained at 3dB.

*(D) Fourth Phase (Production approach)*

Microwave circuits and networks often consist of transmission lines with various types of discontinuities. In some cases discontinuities are an unavoidable result of mechanical or electrical transitions from one medium to another. Some typical microstrip discontinuities and transitions are shown in figure below. Although approximate equivalent circuits have been developed for some printed transmission line discontinuities, many do not lend themselves to easy or accurate modeling, and must be treated by numerical analysis. Modern CAD tools are usually capable of accurately modeling such problems.



AWR simulations that have been realized in third phase do not take these discontinuities into account unless putting some special transition elements of AWR between the sections. In this phase, special transition elements (MSTEPX\$) are inserted between the sections of the transmission lines to eliminate the discontinuities. Figure 2.9 shows this arrangement.



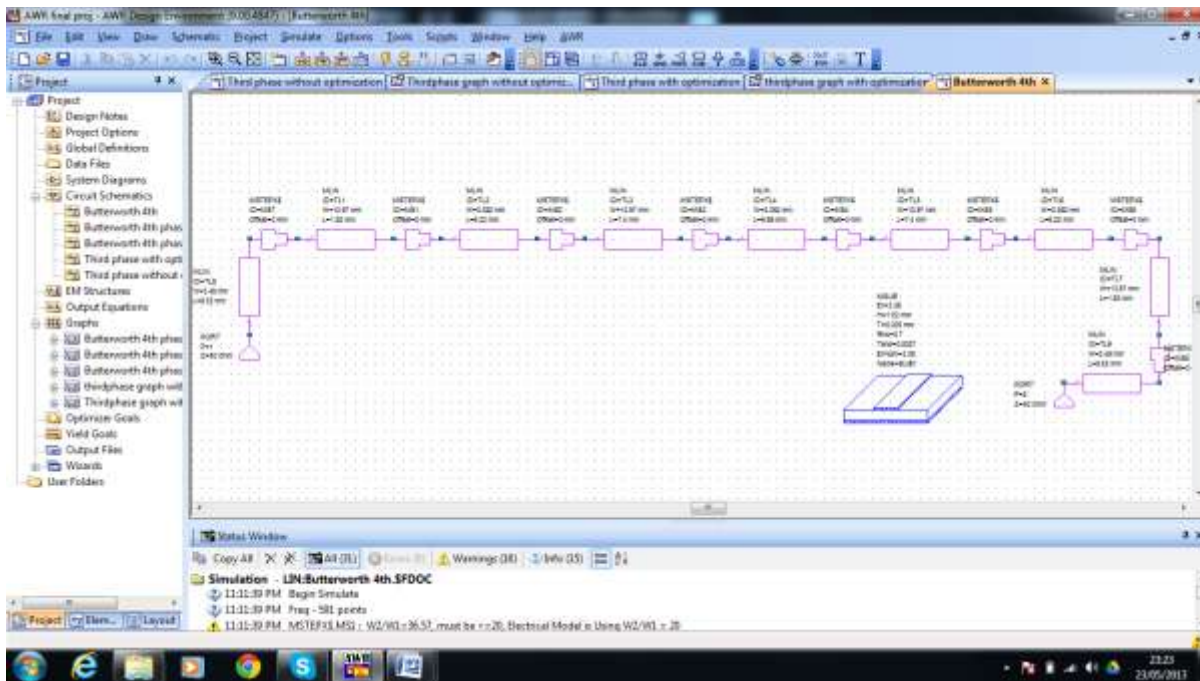


Fig. 2.9(a), AWR simulation of the design with MSTEPX\$ between sections

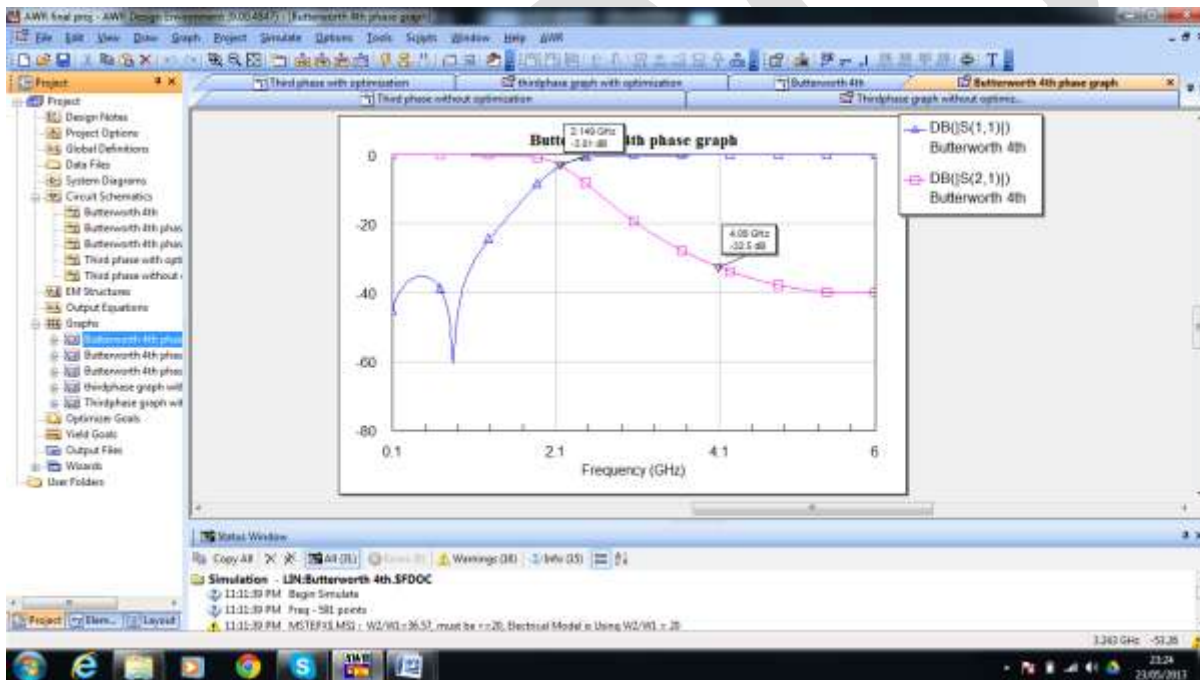


Fig. 2.9(b), graph of S11 and S21 vs frequency with MSTEPX\$ between sections

Looking at the above graph we can see that the cut-off frequency has shifted from 2.4GHz to 2.149GHz. In trying to make the cut-off frequency back to its original value by reducing the lengths of the transmission lines, figure 2.9(c) and (d) were obtained as shown below.

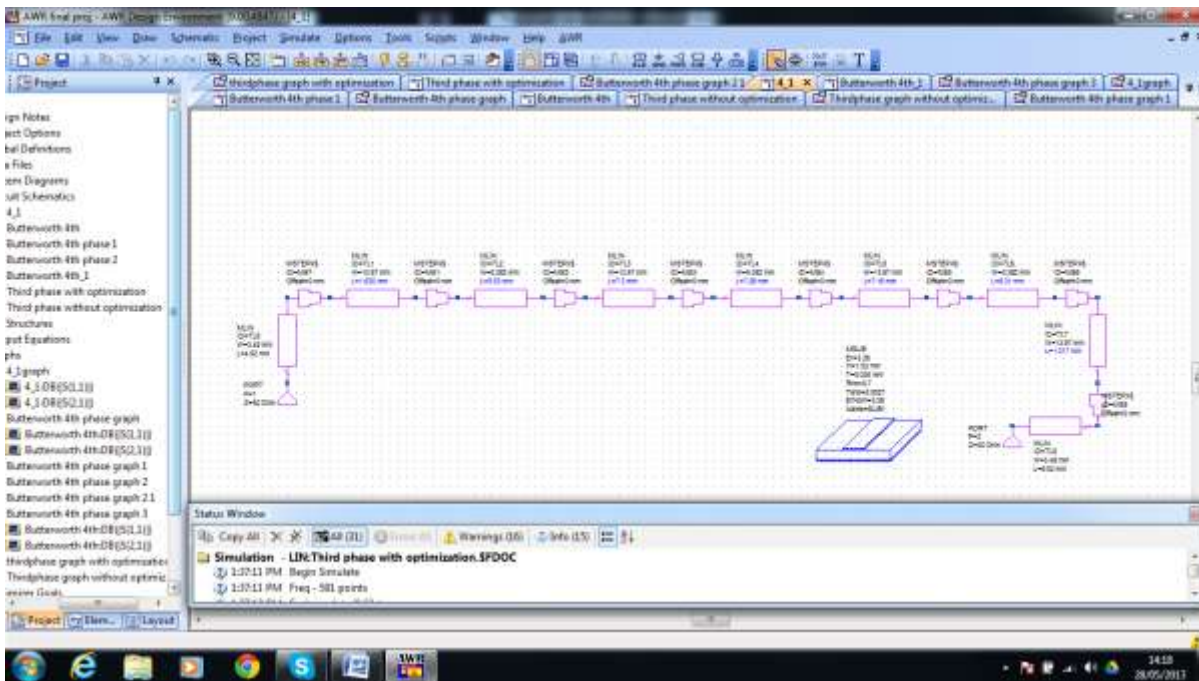


Fig. 2.9(c), AWR simulation with reduced lengths of the transmission lines

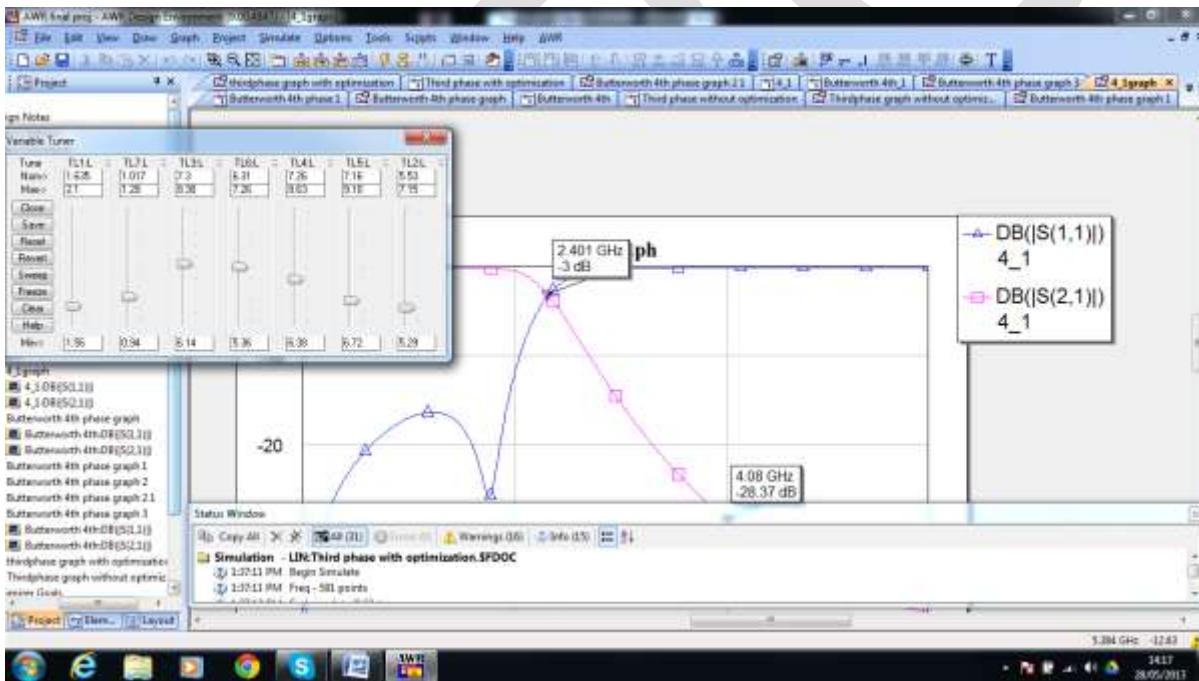


Fig. 2.9(d), graph of S11 and S21 vs frequency with reduced lengths of the transmission lines

By inserting MSTEPX\$ between the sections of the third phase with optimization, the following figures 2.9(e) and (f) were obtained.

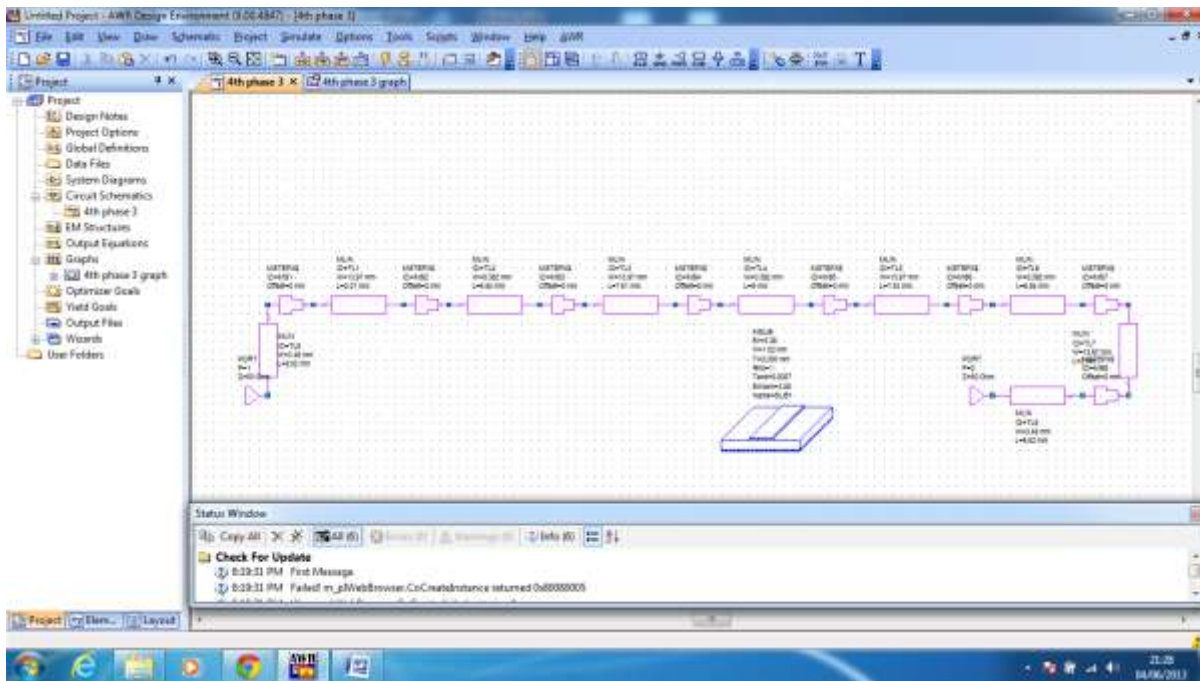


Fig.2.9 (e), AWR simulation of the design with MSTEPX\$ between sections

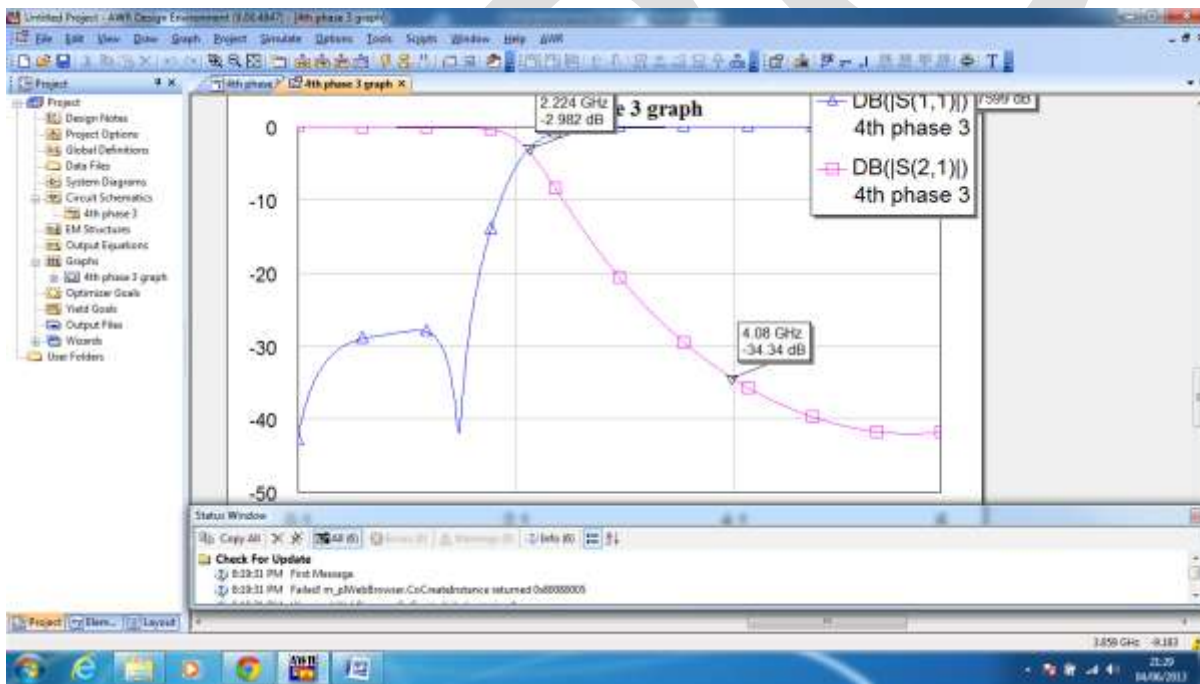


Fig. 2.9(f), graph of S11 and S21 vs frequency with MSTEPX\$ between sections

Finally, by making fine tuning to improve the performance of the filter simulation in third phase with optimization and inserting MSTEPX\$ between sections, figure 2.9 (e) and (f) were obtained as shown below.



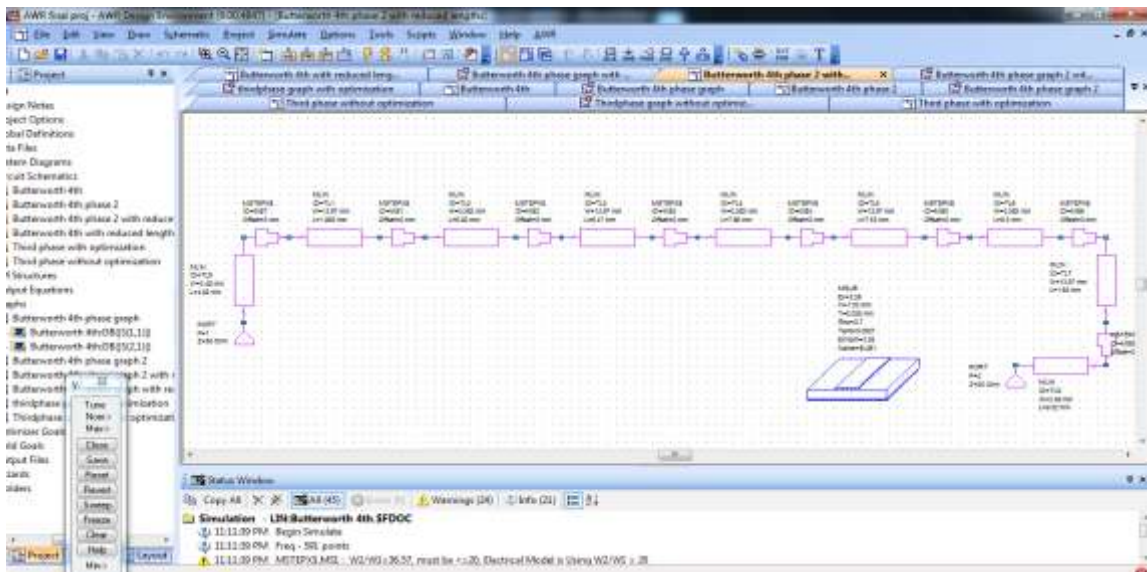


Fig. 2.9 (g), AWR simulation with reduced lengths and MSTEPX\$ between sections

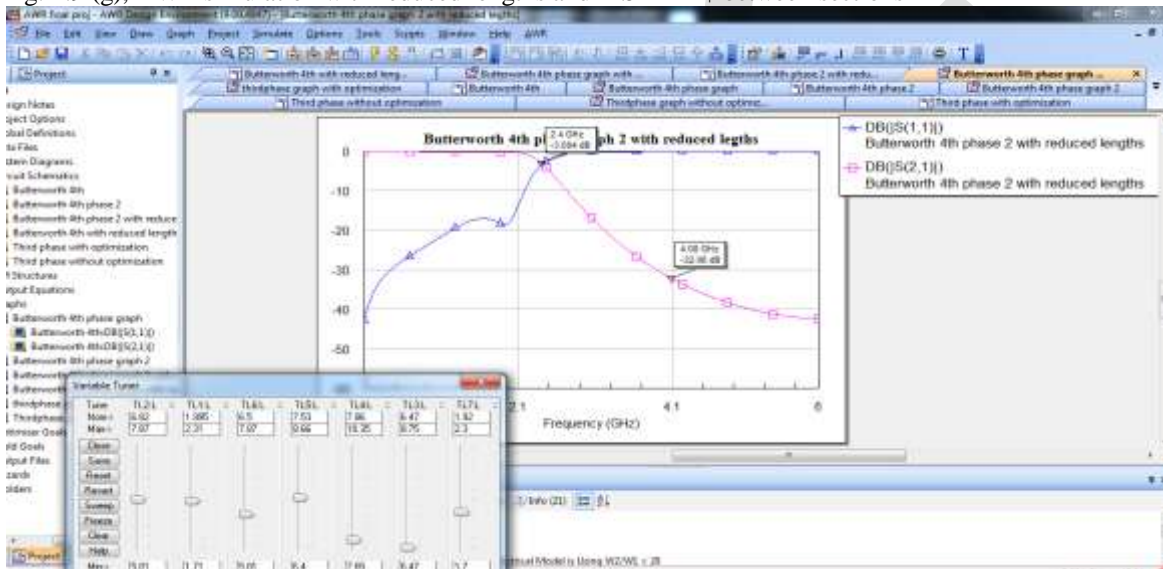


Fig. 2.9 (h), graph of S11 and S21 vs frequency with MSTEPX\$ between sections

**Comment:**

With optimization (tuning), a better result is obtained, here, at 4.08 GHz there is 32.06dB attenuation which is higher than the minimum attenuation specified 30 dB while the cut-off frequency of 2.4 GHz is maintained at 3dB. Table 2.3, below shows the variations of the lengths with insertion of MSTEPX\$ between sections and optimization of the third phase

Table 2.3, optimized and reduced length values of the transmission line

Length of the line	Optimized lengths	reduced in lengths
$l_{cap,1}$	2.01	1.995
$l_{ind,2}$	6.84	6.82
$l_{cap,3}$	7.61	6.47
$l_{ind,4}$	9.00	7.86

$l_{cap,5}$	7.53	7.53
$l_{ind,6}$	6.84	6.50
$l_{cap,7}$	2.00	1.92

## CONCLUSION

In this work, a 7- section Maximally-flat high frequency low-pass filter was designed and simulated using four different phases, (i) Calculation and MATLAB simulations with lumped elements (Approximate solution), (ii) Calculation and MATLAB simulations with microstrip transmission lines (Almost Exact solution), (iii) Implementation of the design on Advancing the Wireless Revolution (AWR) microwave design and optimization/tuning (Engineering solution) and lastly, (iv) Implementation of the design on Advancing the Wireless Revolution (AWR) microwave design by considering discontinuities and optimization/tuning (Practical Solution).

## ACKNOWLEDGMENT

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