World Wide Journal of Multidisciplinary Research and Development (October-2022)

WWJMRD 2022; 8(10): 67-80
www.wwjmrd.com
International Journal
Peer Reviewed Journal
Refereed Journal
Indexed Journal
Impact Factor SJIF 2017: 5.182 2018: 5.51, (ISI) 2020-2021: 1.361
E-ISSN: 2454-6615

Animiosevbuse Tosan Enoma
Department of
Electrical/Electronic
Engineering, Niger Delta
University, Nigeria.

Tebe Larry Ojukonsin
Department of
Electrical/Electronic
Engineering, Niger Delta
University, Nigeria.

Ayibapreye Kelvin Benjamin
Department of
Electrical/Electronic
Engineering, Niger Delta
University, Nigeria.

Correspondence:
Animiosevbuse Tosan Enoma
Department of
Electrical/Electronic
Engineering, Niger Delta
University, Nigeria.

MATLAB Based Stepped Impedance Microstrip Filter Design using Advanced Design Systems

Animiosevbuse Tosan Enoma, Tebe Larry Ojukonsin, Ayibapreye Kelvin Benjamin

Abstract

This paper describes an advanced design systems (ADS) approach of stepped impedance microstrip low pass filter design for both maximally flat or Butterworth and Chebyshev responses. The cut-off frequency is 4 GHz with source and load impedances of $50\,\Omega$. The insertion loss at passband is $0.5\,dB$ and stopband is $20\,dB$. In this filter design, an order $N = 5$ was used for computation of the lumped elements of Chebyshev low pass filter prototype and $N = 7$ was chosen for maximally flat (Butterworth) filter prototype. Substrate properties such as relative dielectric constant $\in_r = 4.2$, loss tangent $tan\delta = 0.02$, height of dielectric material $h = 2.0\,mm$ and conductor thickness of $0.01\,mm$ were used in calculation of the length and width of the transmission line. MATLAB was used in plotting variations of Maximally flat and Chebyshev responses as functions of filter order N, transfer function parameter e and angular frequency ω in rad/s. Design of lumped circuit for microwave filter prototype scaled in frequency and impedances is discussed. Equivalent transmission line was obtained by converting lumped circuit into certain lengths and characteristic impedances. ADS simulation software was used to plot filter characteristics of both maximally flat and Chebyshev responses. The plots show variation of incident wave $S(1,1)$ and forward gain $S(1,2)$ with frequency in GHz. It also fabricates microstrip structural layouts for maximally flat and Chebyshev filters.

Keywords: MATLAB, Stepped Impedance, Microstrip, Filter, ADS.

1.0 Introduction

Microwave filters are two-port network used to control the frequency response at certain point in a microwave system by signal transmission at frequencies within the passband of the filter and attenuation within the stopband of the filter. The incessant increase in demand and specification levels of microwave filters for advanced communication systems have necessitated research interest in both industry and academia. Hence, microwave filter designs are becoming very popular [1]-[6].

Maximally flat (Butterworth) filter, Chebyshev filter and Bessel filter are realizable filters often used in the design of microwave low-pass filter. The use of maximally flat low-pass filter raises contradiction concerns between stability, response time and test precision. Maximally flat filter with low order N has characteristics such as small filter overshoot, rapid response and bad test precision. Higher order maximally flat low-pass filters have good test precision, large overshoot, poor stability and slow response [5]-[6]

This filter has a type of construction called reflective filter and consists of capacitive and inductive elements that gives ideally zero reflection loss in the passband region and very high attenuation in the stopband region. An ideal or perfect filter do not exist in practice, to achieve a near ideal filter compromises are made which are inherent in filter design. A perfect filter should have zero insertion loss in the passband, infinite attenuation in the stopband, and in the passband-a linear phase response to avoid signal distortion [6]-[7].

Shreyasi. et.al [8]-[13] presented the design technique, fabrication, simulation and comparison between measured and simulated results of microstrip parallel coupled bandpass filter. This was designed and optimized at $2.44\,GHz$ with a fractional bandwidth (FBD) of $3.42\,\%$. The usual design procedure of first calculating the lumped components and develop its prototype was adopted. Shreyasi et. al used an admittance inverter to transform the lumped circuit into an equivalent distributed circuit using microwave structures. Filter specifications such width w, thickness h and dielectric constant of substrate $\in$ were used to realize the filter structure using parallel coupled technique. Advanced design systems (ADS) software was used in simulating microstrip filter characteristics. An optimization was carried out to obtain low insertion loss and selective skirt. The filter was fabricated on Flame Retardant (FR-4) and comparison between simulated and measured results were reported. The insertion loss for test results were slightly more $(1.5\ dB)$ than the simulated results which may be due to fabrication anomalies, FR-4 material losses and disparity in dielectric constants can be attributed to the reason for higher insertion loss.

Ninikrishna et. al [14]-[15] designed a microstrip low-pass filter by insertion loss method using two electrical lengths of $230°$ and $90°$ $(^{\lambda}/_{4})$ transmission lines. Repeating characteristics of low-pass filter amplitude response was obtained using Richardson's transformation. To obtain sharp rejection within a cut-off frequency of $10\ GHz$ which was highest, the electrical length was $90°$. Ninikrishna et. al used an analysis technique very effective for harmonic suppression, and have spurious frequencies in the stopband. It is widely deployed for radar applications. Realization of the low-pass filter was achieved by the use of distributed elements that were obtained by various transformations such as Richard's transformation, Kuroda's identity and the concept of unit elements. This design gives a perfect property of low insertion loss in the passband and infinite attenuation in the stopband.

A modification of stepped-impedance microstrip realization method was proposed and fabricated by [14] using the open circuited stub microwave realization method. This approach approximates the series inductance as a high impedance transmission line and the shunt capacitance effect is simulated by an open circuited stub via Richard's transformation. Jubril et. al proposed design of a $2\ GHz$ maximally flat low-pass filter (LPF) was fabricated on a FR4 dielectric substrate using open-circuited stubs and approximates the lumped circuit model. Simulation of this filter was compared with laboratory measurements for insertion loss and appears consistent. Filter design specification was met as $-3.009\ dB$ attenuation was achieved at the cut-off frequency $(2\ GHz)$ and $-19.359\ dB$ attenuation was obtained at $4\ GHz$. Filter performance was very close and its loop characteristics exceeded the design specification. Easy turning of the stopband performance can be provided by the open-circuited stub filter by varying the length of stub [14].

Recently developed microwave filters are designed by the insertion loss method. This approach approximates the amplitude response of the filter using network synthesis method that was advanced to incorporate microwave distributed circuit elements. In this design, an adopted four step procedure is used: filter specification, low-pass filter prototype design, frequency scaling and impedance transformation of the filter, and implementation (conversion of lumped elements to distributed elements) using ADS software [15].

Due to the incessant demand to meet ever-growing telecommunication challenges faced by microwave systems due to size, cost and performance of microwave devices, there is need to design microstrip low-pass filters that transmit signals at microwave frequency. In this project, a microstrip stepped impedance low-pass filter with insertion loss of $0.5\ dB$ at cut-off frequency $4\ GHz$ and attenuation of $20\ dB$ at stopband frequency $6\ GHz$, with given substrate properties such as relative dielectric constant $\in_r = 4.2$, loss tangent $tan\delta = 0.02$, height of dielectric material $h = 2.0\ mm$ and conductor thickness of $0.01\ mm$ was designed for order $N = 7$ maximally flat (Butterworth) filter low-pass prototype and $N = 5$ Chebyshev low pass filter prototype. This designed was projected to achieve a harmonic suppression of $-20\ dB$ at stopband frequency of $6\ GHz$. Here, we report the design of a stepped-impedance microwave filter using advanced design system (ADS). The design was carried out with a cut-off frequency or passband frequency of $4\ GHz$ and stop band frequency of $6\ dB$ with input and output impedance of $50\ \Omega$.

2. Methodology

2.1 Stepped Impedance low-pass filter design procedure

Simulation of lumped elements in the filter circuit can be realize using waveguides, coaxial lines, strip or microstrip lines, cavity resonators, etc. The equivalent circuit which comprised of lumped element values of the microwave components are mainly functions of frequency. Microwave filter design of various types operating at arbitrary frequency bands and within arbitrary resistive loads, are developed from a prototype low-pass design through

1. Frequency transformers.
2. Normalization of lumped elements and its simulation through sections of transmission lines.
3. Design of low-pass filter prototype with unique passband characteristics.
4. The prototype network is transformed to the specified type (low-pass, high-pass, and band-pass) filter with the cut-off and stopband frequencies.

The distributed network in microwave form is realized using sections of microwave transmission lines.

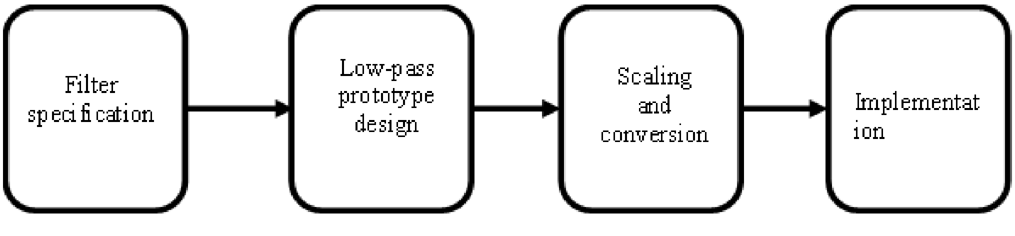


Fig. 1: Filter design procedure by insertion loss method.

2.2. Filter Specification

We assume a cut-off frequency of $4\ GHz$ and stopband frequency of $6\ GHz$. Source and load impedances of $50\ \Omega$ was used for this design. Insertion loss at passband is

$0.5\ dB$ and $20\ dB$ at stopband. Chebyshev low-pass filter response with order $N = 5$ was considered while maximally flat or Butterworth filter prototype with order $N = 7$ was used in this design, with a practically highest line impedance of $Z_h = 120\ \Omega$ and lowest of $Z_l = 20\Omega$. The effect of losses was taken into consideration when implementing this filter design with microstrip substrate of height $h = 2.0\ mm$, $\in_r = 4.2$, loss tangent $tan\delta = 0.02$, and copper conductors of thickness $T = 0.01\ mm$.

2.3. Low Pass Filter Design

Beyond frequency of $500\ MHz$, it is challenging to design microwave filters using lumped elements as the physical dimensions of the filter are comparable to wavelength. This results in losses at different levels causing degradation of circuit performance. Richard's transformation is used to convert the lumped elements into distributed elements circuit. Kuroda's identities are used to solve the distance between components problem which is negligible at high microwave frequencies. This can be done by separating filter elements by inserting transmission line sections.

Figure 2 to Figure 5 illustrate filter characteristic of both maximally flat response and chebyshev filter as functions of frequency, order and transfer function parameter e. $N = 3$ was the order of the filter used for both the maximally flat and the chebyshev filters in Figure 2.

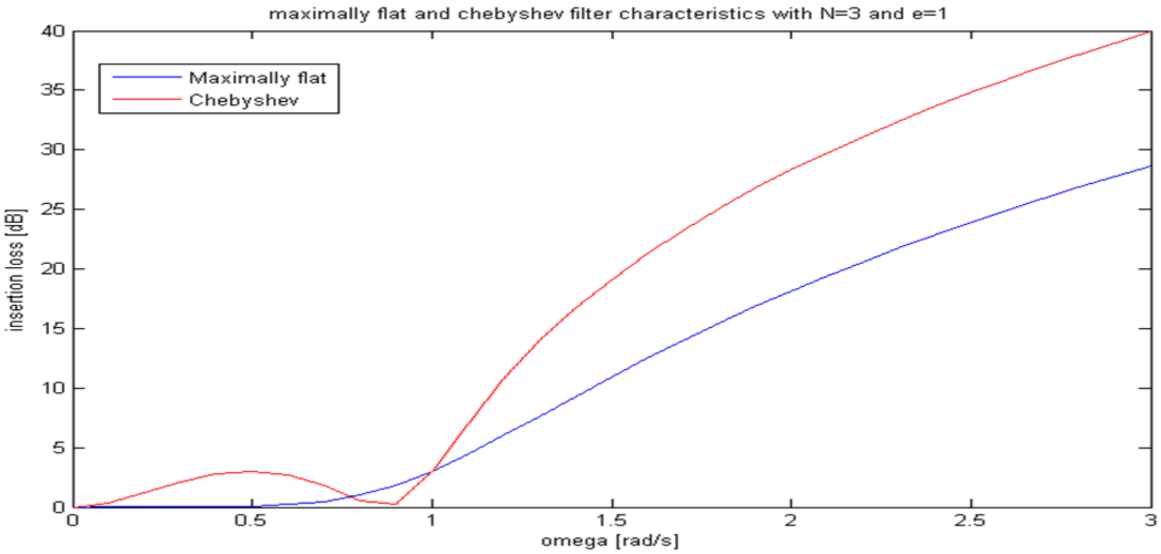


Fig. 2: Maximally flat filter and chebyshev filter characteristics with $N = 3$ and $e = 1$.

For the maximally flat filter, there was a gradual increase in the height as shown above, while the chebyshev suffered a ripple at the beginning. Another difference is that the chebyshev filter has a higher insertion loss compared to the maximally flat filter for the same order.

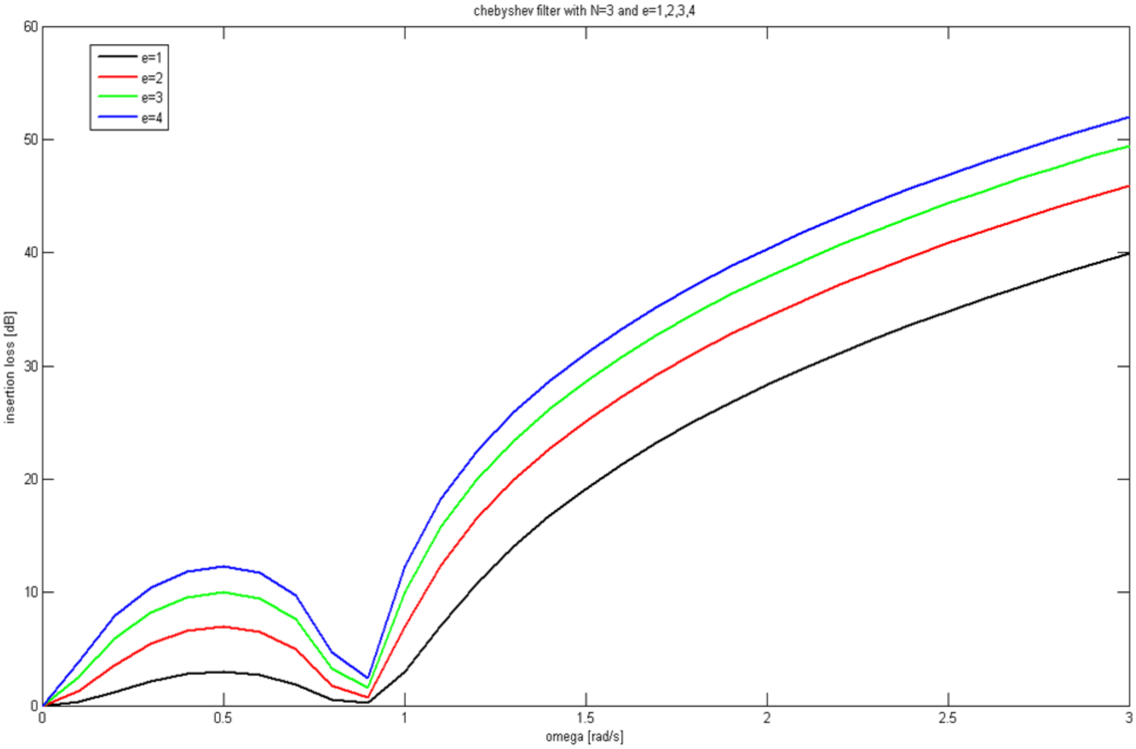


Fig. 3: Chebyshev filter with $N = 3$ and $e = 1,2,3,4$.

The peak of the ripple formed increases as the parameter e increases. This implies that the higher the value of e, the higher the insertion loss and the higher the peak of the ripples too.

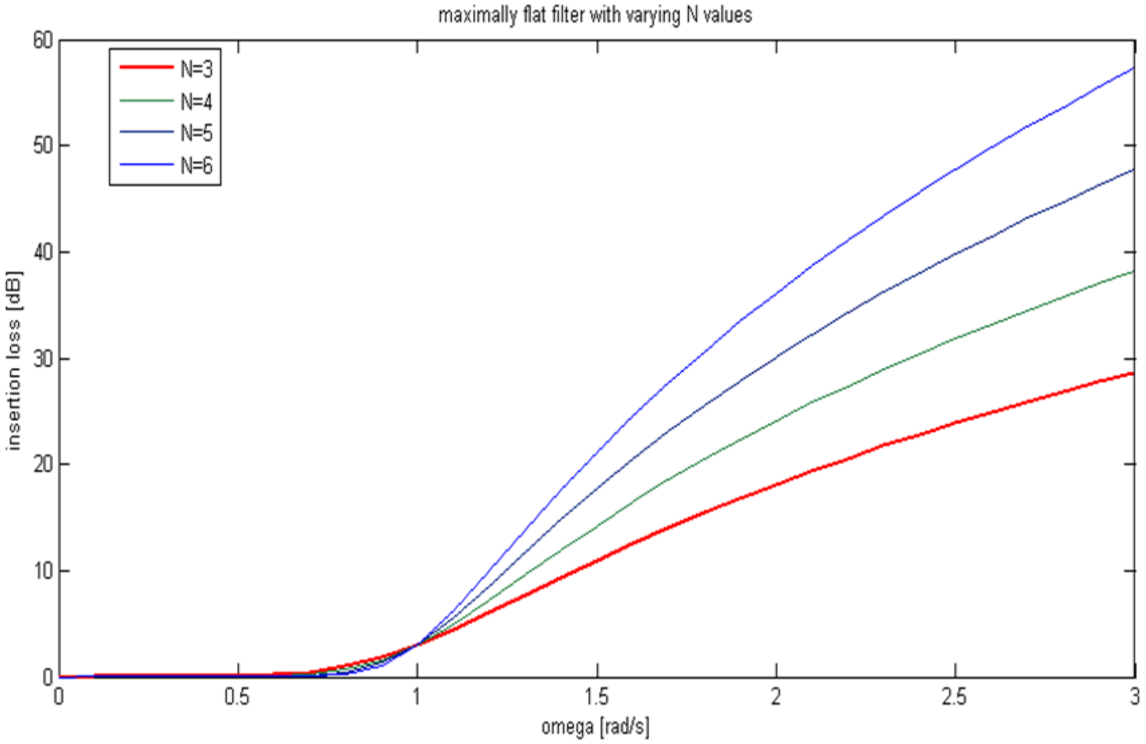


Fig. 4: Maximally flat filter with varying N values

Figure 4 shows that the insertion loss increases with increasing order N. When $N = 3$, insertion loss is approximately 29.89 dB; whereas when $N = 6$, insertion loss is around 57 dB. This also increases with increasing omega. It is called maximally flat because closer to the origin; it is flat until at omega greater than 0.7 rad/s, it starts increasing.

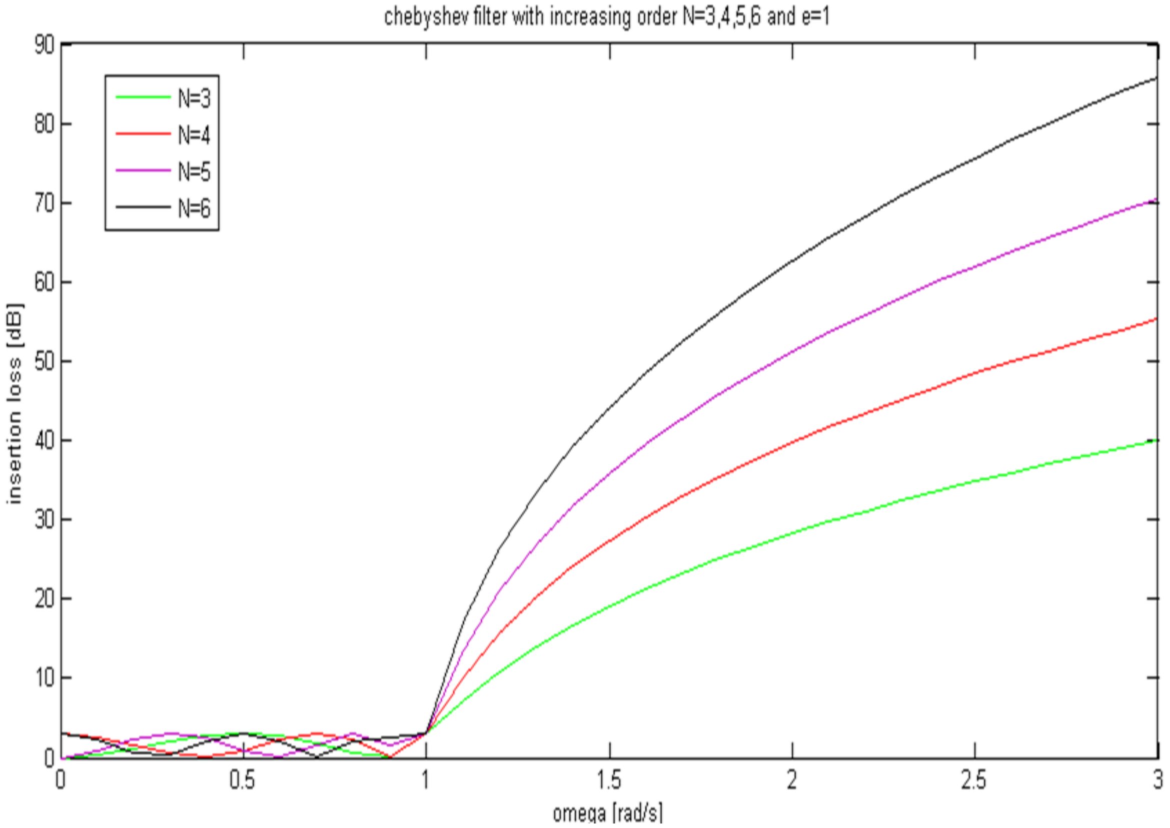


Fig 5: Chebyshev filter increasing order $N = 3,4,5,6$ and $e = 1$.

For figure 5, the insertion loss increases with increasing order N. When $N = 3$, insertion loss is approximately $40\ dB$; whereas when $N = 6$, insertion loss is around $86\ dB$. This also increases with increasing omega. From the origin of the plot, we can see ripples until at omega greater than 1 rad/s, it starts increasing.

2.4 Design of Maximally Flat Low-Pass Filter

The appropriate order of filter, N is determined for given filter specifications. For maximally flat filter characteristic we can obtain the order of the filter that satisfies characteristics by:

$$N \geq \frac{IL(\omega_c) + IL(\omega_s)}{20 \log\left(\frac{\omega_s}{\omega_c}\right)} \tag{1}$$

Insertion loss at ω_c $\left(IL(\omega_c)\right) = 0.5dB$

Insertion loss at ω_s $\left(IL(\omega_s)\right) = 20dB$

The cut-off frequency or passband frequency = 4 GHz

The stopband frequency = 6 GHz

$$N \geq \frac{0.5dB + 20dB}{20 \log\left(\frac{6}{4}\right)} \tag{2}$$

$$N \geq \frac{20.05dB}{20 \log(1.5)} \tag{3}$$

$$N \geq 5.82. \tag{4}$$

Odd number filters give better roll-off and frequency response and higher order helps to provide low attenuation at high frequency. Hence, the need to choose an order of 7 instead of 5.

Table 1: Shows element values for maximally flat low-pass filter prototype ($g_o = 1, \omega_c = 1, N = 7$)

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
7	0.4450	1.2470	1.8019	2.0	1.8019	1.2470	0.4450	1.0

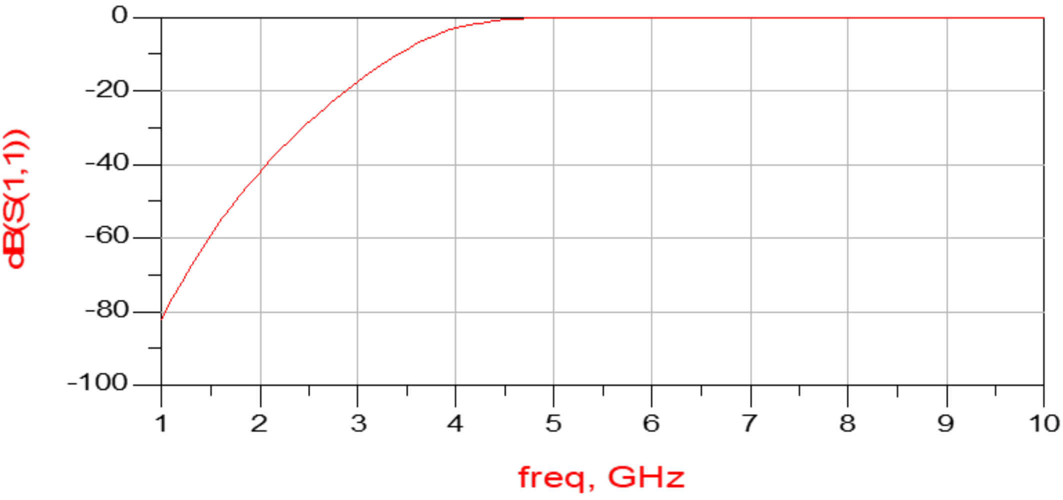


Fig. 6: The characteristic of the microwave filter showing variation of incident wave with frequency.

Fig. 7: The characteristic of the microwave filter showing variation of the forward gain with frequency.

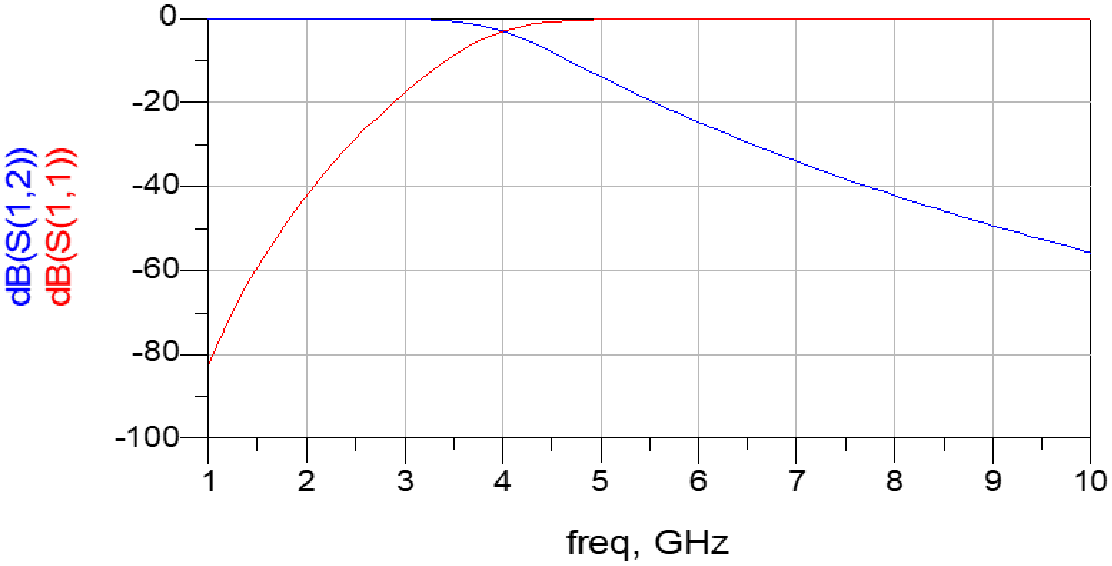


Fig. 8: The characteristic of the microwave filter showing variation of both incident wave and the forward gain with frequency.

This explains the fact that the microwave filter design met the specification of the maximally flat low-pass filter design specification as the incident wave and forward gain intercept at 4 GHz. In Figure 6 and Figure 8 the cut-off frequency of 4 GHz was obtained.

2.5 Design of Microwave Filter Prototype (L and C Elements) Scaled for the Given Frequency Band and 50Ω Input and Output Impedance.

The coefficients were converted into a microwave prototype network by impedance and frequency scaling utilizing the equations as follows:

$L' = \frac{R_O L}{\omega}$, $C' = \frac{C}{R_O}$, $\beta l = \frac{L'}{Z_{OL}}$, given that $R_O = 50\Omega$, $\omega_c = 2\pi f_c$, f_c= 4 GHz

Table 2: Shows lumped element values of the capacitor and inductor for maximally flat low pass filter prototype ($g_o = 50\Omega$, $g_8 = 50\Omega$)

g_o	$g_1 - L_1$	$g_2 - c_1$	$g_3 - L_2$	$g_4 - c_2$	$g_5 - L_3$	$g_6 - c_3$	$g_7 - L_4$	g_8
50Ω	0.885 nH	0.992 pF	3.538 nH	1.592 pF	3.585 nH	0.992 pF	0.885 nH	50 Ω

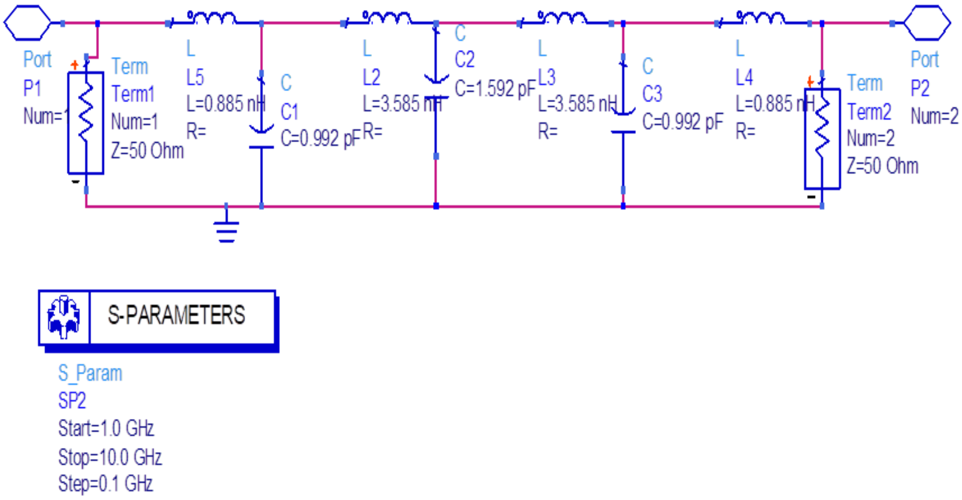


Fig. 9: Lumped circuit for maximally flat low-pass filter prototype obtained from ADS software.

2.6 Equivalent Transmission Line Filter obtained by Converting the Capacitors and Inductors of the Lumped Circuit into Transmission Lines of Certain Lengths and Characteristic Impedances.

To obtain the equivalent transmission line filter we have to convert the capacitors and inductors of the lumped circuit into transmission lines of certain lengths and characteristic impedances. This is obtained by the equations below;

$L' = R_O L$, $C' = \frac{C}{R_O}$, $L = Z_{OL}\beta l, C = \frac{\beta l}{Z_{OC}}$, $where\ R_O = 50\Omega$

From these calculations the above transmission line parameters were obtained as shown in Table 3.

Table 3: Equivalent line filter characteristics.

Low pass prototype	Impedance scale	Electrical-length $(\beta l) in\ degrees$
$L_1 = 0.4450$	22.250	10.62
$C_1 = 1.2470$	0.0250	28.57
$L_2 = 1.8019$	90.095	43.02
$C_2 = 2.0$	0.040	45.84
$L_3 = 1.8019$	90.095	43.02
$C_3 = 1.2470$	0.0250	28.57
$L_4 = 0.4450$	22.250	10.62

The ADS software enables us to represent the above transmission line parameters in circuit format as the values are applied for short circuit and open circuit sections of the transmission line.

Below is the transmission line distributed circuit.

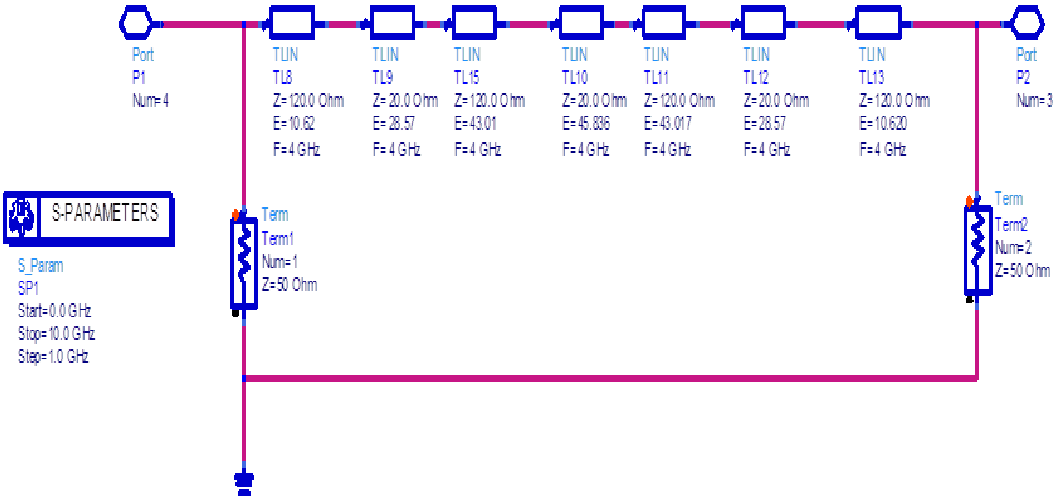


Fig. 10: ADS representation of the distributed transmission line circuit

The characteristic of the distributed transmission line circuit was obtained by simulating the circuit using the ADS software and we were able to obtain similar frequency response as compared to the lumped maximally flat low-pass filter prototype. We obtained a cut-off of 4 GHz for both s_{11} and s_{12} against frequency. It is of great importance to note that, s_{12} and $s_{21} are\ symetrically\ equal$. It was observed that when s_{12} and s_{21} was plotted on the same axis against frequency there was an interception at 4GHz which proves the fact that the design specification was achieved. The frequency responses of s_{12} and s_{21} are shown below.

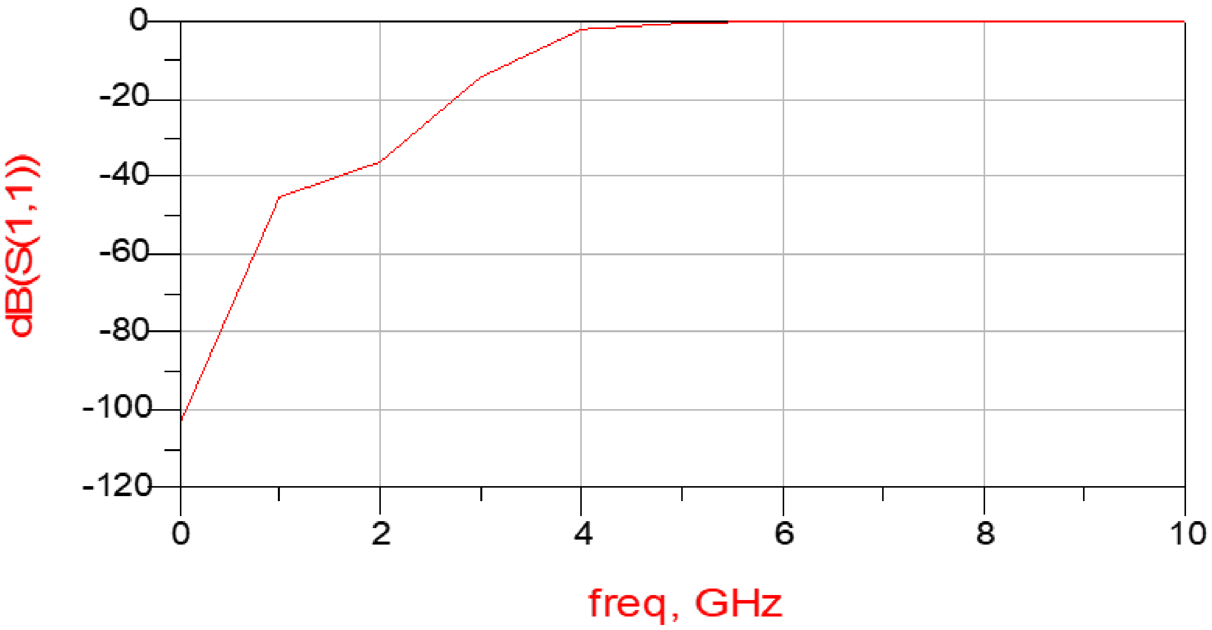


Fig. 11: The characteristic of distributed transmission line showing variation of incident wave with frequency

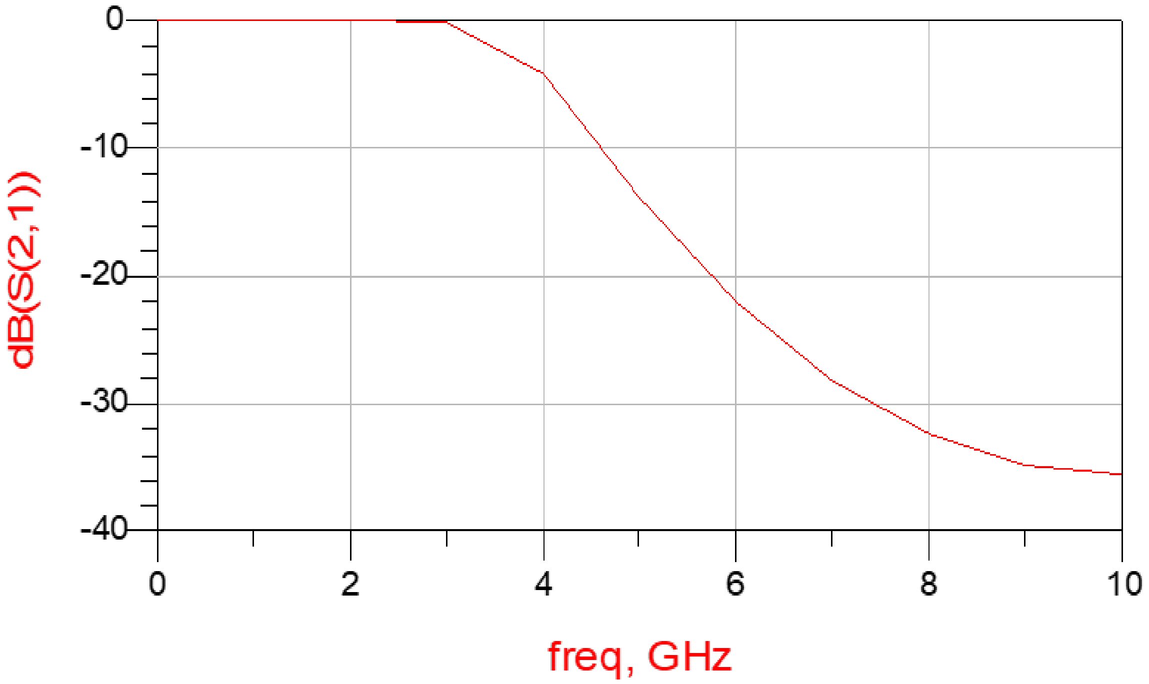


Fig. 12: The characteristic of distributed transmission line showing variation of reversed gain with frequency

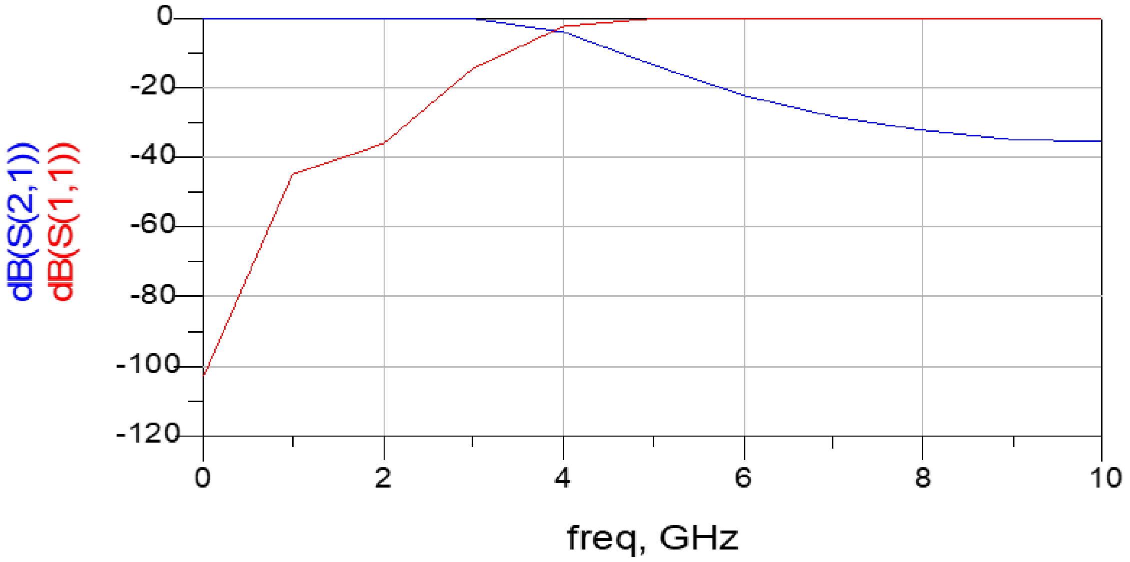


Fig. 13: The characteristic of the distributed transmission line showing variation of both incident wave and the reversed gain with frequency

To select the appropriate low-pass prototype network, it is necessary to calculate the appropriate order N for the Chebyshev filter:

$$N \geq \frac{IL(\omega_c) + IL(\omega_s) + 6}{20\log\left(p + \sqrt{p^2 - 1}\right)} \qquad (5)$$

$$\text{where } p = \frac{\omega_s}{\omega_c} = \frac{6}{4} = 1.5$$

$$N \geq \frac{0.5 + 20 + 6}{20\log\left(1.5 + \sqrt{1.5^2 - 1}\right)} \qquad (6)$$

$$N \geq 3.17 \qquad (7)$$

It is better to choose a higher order chebyshev filter as it gives better frequency response at high frequency and odd number filter is better than even number. Hence, an odd number order of 5 is used.

Table 4: shows element values for chebyshev low pass filter prototype ($g_o = 1, \omega_c = 1, N = 5$)

N	g_1	g_2	g_3	g_4	g_5	g_6
5	1.7058	1.2296	2.5408	1.2296	1.7058	1

Fig. 14: The characteristic of the chebyshev filter showing variation of incident wave with frequency.

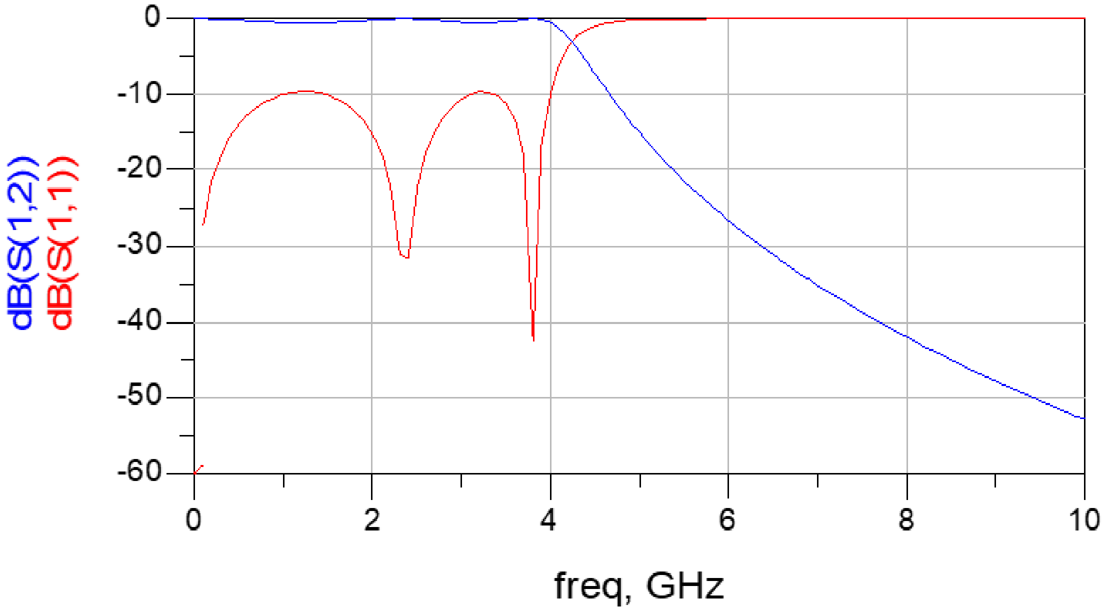


Fig. 15: The characteristic of the chebyshev filter showing variation of both incident wave and the forward gain with frequency.

3.0 Results and Discussions

3.1 Layout of the Microstrip Structure for Maximally Flat (Butterworth) Filter

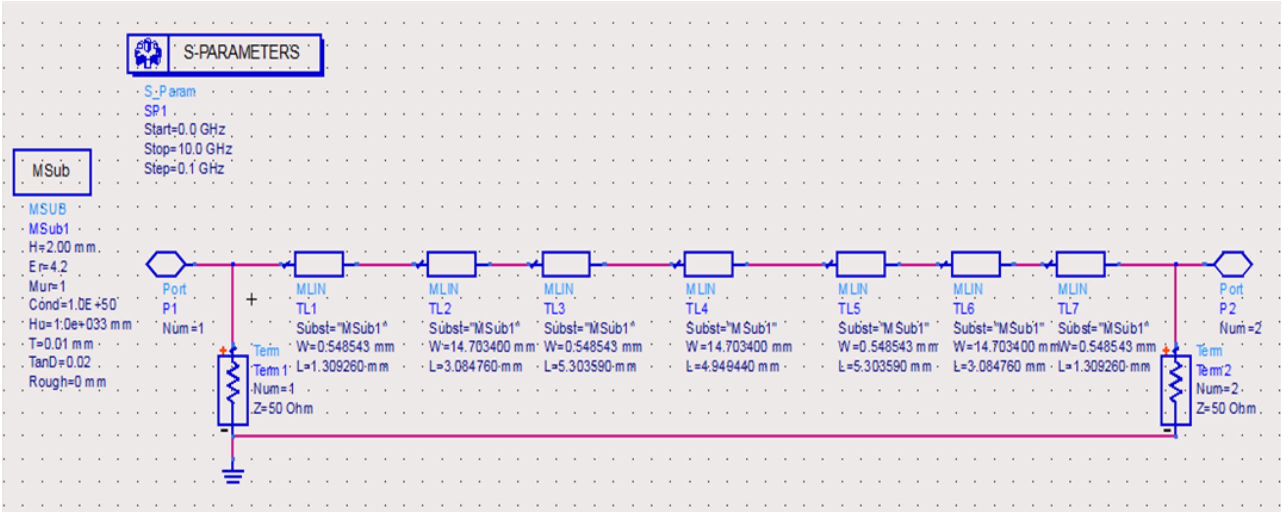
Based on the assumption that all transmission lines are realized in microstrip technology and the substrate has dielectric constant $\varepsilon_r = 4.2$, rough= 0 mm, mur=1, H = 2.0 mm, Hu =1.0, cond=1.0e+5, tanδ=0.02, T=0.01mm and using the above equations;

$$L' = R_O L,\ C' = \frac{C}{R_O}, \qquad L = Z_{OL}\beta l, C = \frac{\beta l}{z_{oc}}, where\ R_O = 50\Omega$$

We were able to estimate the width and the length of the individual microstrip line.

Distributed component	Impedance scale	Electrical-length (βl) $in\ degrees$	Width (mm)	Length(mm)
L_1	22.250	10.62	0.549	1.309
C_1	0.0250	28.57	14.70	3.085
L_2	90.095	43.02	0.549	5.304
C_2	0.040	45.84	14.70	4.950
L_3	90.095	43.02	0.549	5.304
C_3	0.0250	28.57	14.70	3.085
L_4	22.250	10.62	0.549	1.309

Below is an ADS representation of the microstrip filter structure.



S_Param
SP1
Start=0.0 GHz
Stop=10.0 GHz
Step=0.1 GHz

MSUB
MSub1
H=2.00 mm
Er=4.2
Mur=1
Cond=1.0E+50
Hu=1.0e+033 mm
T=0.01 mm
TanD=0.02
Rough=0 mm

Port
P1
Num=1

Term
Term1
Num=1
Z=50 Ohm

MLIN
TL1
Subst="MSub1"
W=0.548543 mm
L=1.309260 mm

MLIN
TL2
Subst="MSub1"
W=14.703400 mm
L=3.084760 mm

MLIN
TL3
Subst="MSub1"
W=0.548543 mm
L=5.303590 mm

MLIN
TL4
Subst="MSub1"
W=14.703400 mm
L=4.949440 mm

MLIN
TL5
Subst="MSub1"
W=0.548543 mm
L=5.303590 mm

MLIN
TL6
Subst="MSub1"
W=14.703400 mm
L=3.084760 mm

MLIN
TL7
Subst="MSub1"
W=0.548543 mm
L=1.309260 mm

Term
Term2
Num=2
Z=50 Ohm

Port
P2
Num=2

Fig. 16.: ADS microstrip structure.

After simulating the ADS, the following characteristics of the microstrip were obtained and the microstrip layout was obtained.

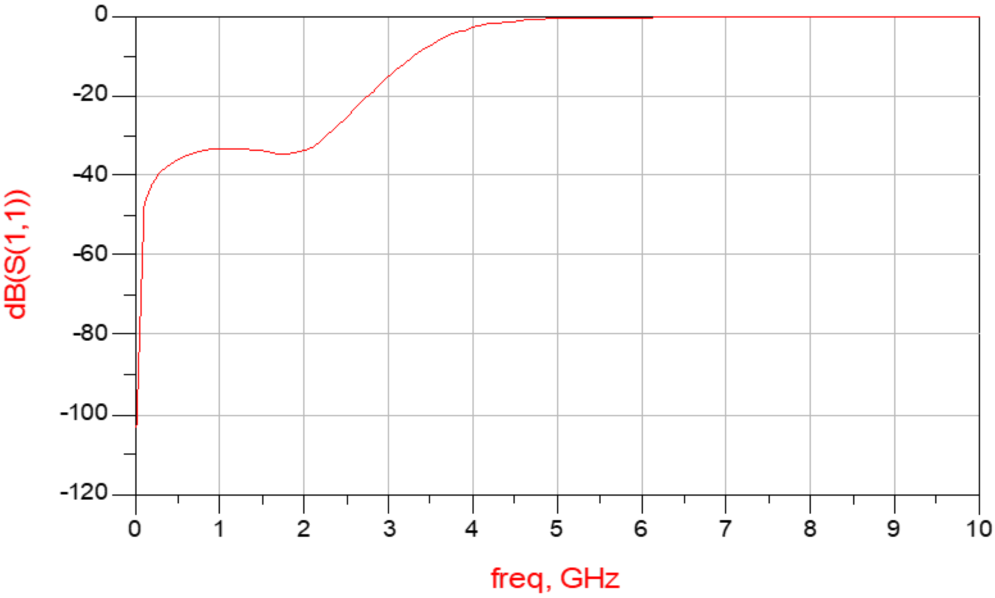


Fig. 17: The characteristic of microstrip structure showing variation of incident wave with frequency.

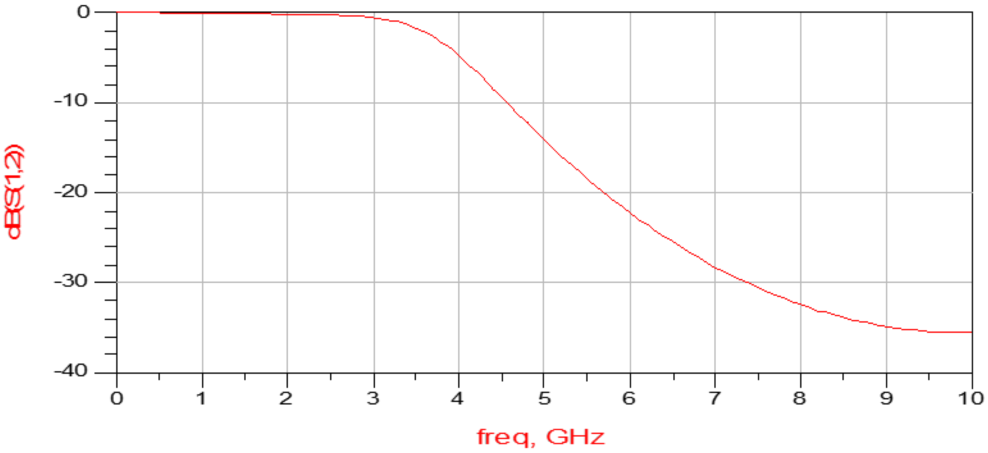


Fig. 18: The characteristic of microstrip structure showing variation of reversed gain with frequency.

The impulse response is not symmetric and as a result, the filter does not have a linear phase response. It can be seen that some of the widths are extremely thin and might be very hard to actually make in reality. This is one of the limitations of the stepped impedance filter design.

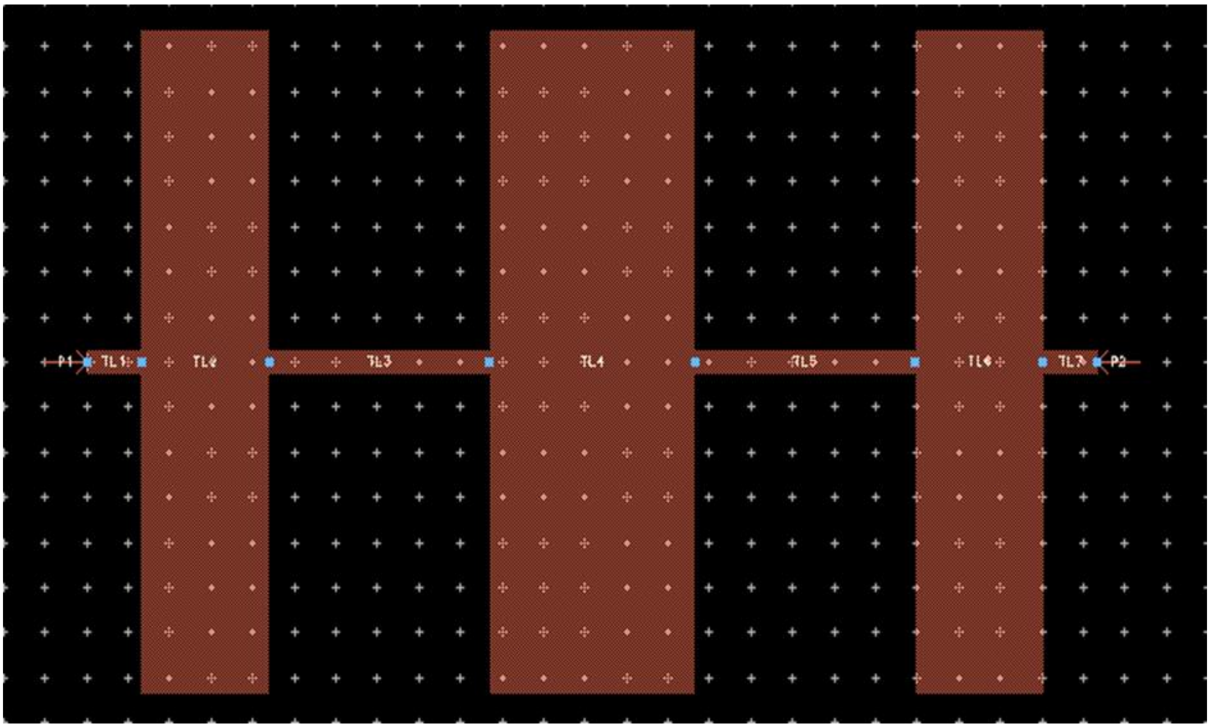


Fig. 19: The microstrip filter structure for the maximally flat filter.

The Chebyshev filter provides a slightly faster roll-off in the transition band than the maximally flat gain filter. The maximally flat filter has wide transition band. A higher order Chebyshev filter is required to meet the same filter specification as maximally flat filter. The maximally flat filter response is smooth at the passband while that of the Chebyshev filter is equi-rippled at the passband. They both meet the design specification of the filter. The point of intersection of S(1,1) and S(2,1) which is the cut-off point is not exactly at the 4 GHz frequency mark.

3.2 Layout of the Microstrip Structure for Chebyshev Filter

Based on the assumption that all transmission lines are realized in microstrip technology and the substrate has dielectric constant $\varepsilon_r = 4.2$, rough = 0mm, mur =1, H =2.0 mm, Hu =1.0, cond =1.0e+5, tanδ = 0.02, T = 0.01mm and using the above equations;

$L' = R_O L,\ C' = \frac{C}{R_O},\qquad L = Z_{OL}\beta l, C = \frac{\beta l}{z_{oc}}\ ,where\ R_O = 50\Omega$

We were able to estimate the width and the length of the individual microstrip line

Sections	Z	*βl*	W(mm)	*l(mm)*
1	120	40.72°	0.5352	4.939
2	20	28.19°	14.56	3.0183
3	120	60.66°	0.535	7.424
4	20	28.19°	14.56	3.018
5	120	40.72°	0.536	4.939

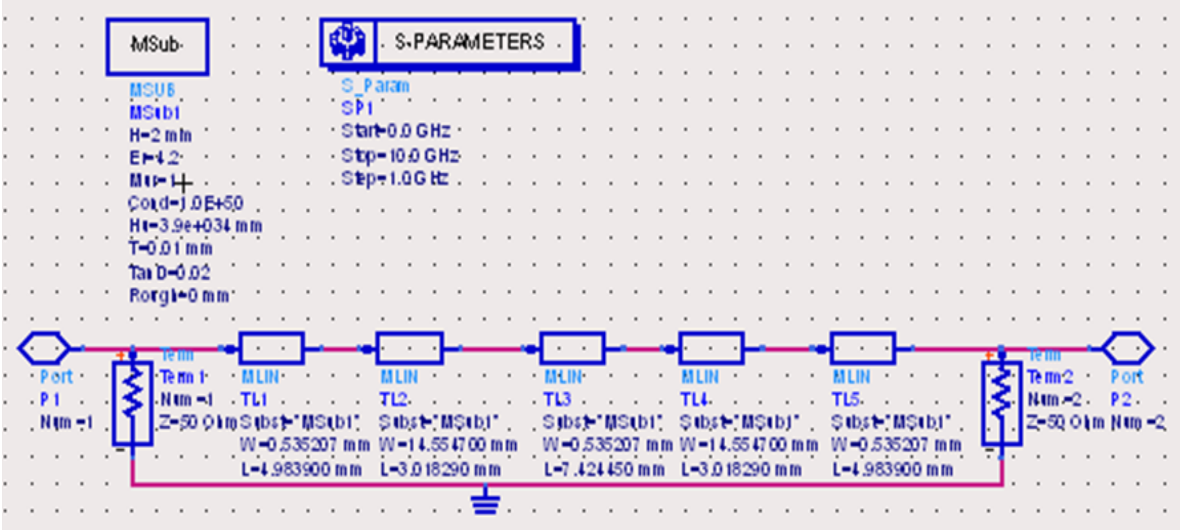


Fig. 20: ADS representation of the Chebyshev microstrip filter.

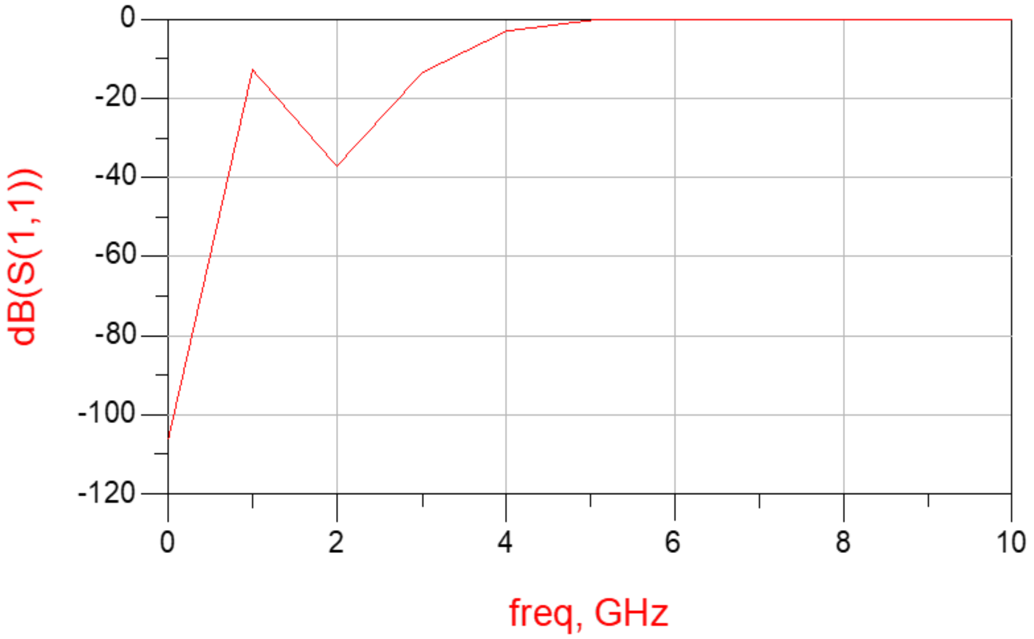


Fig. 21: The characteristic of microstrip structure showing variation of incident wave with frequency.

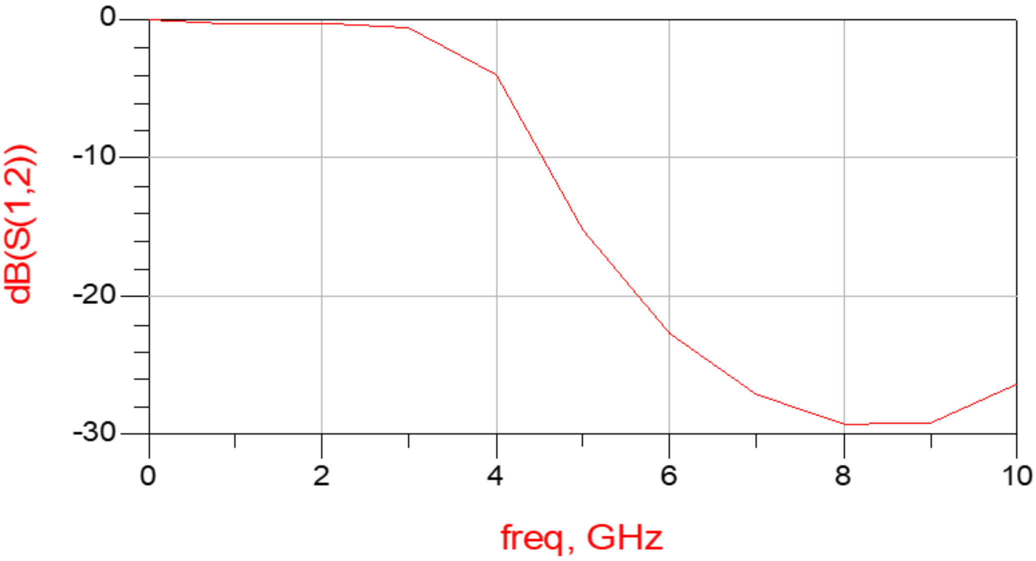


Fig 22: The characteristic of microstrip structure showing variation of reversed gain with frequency.

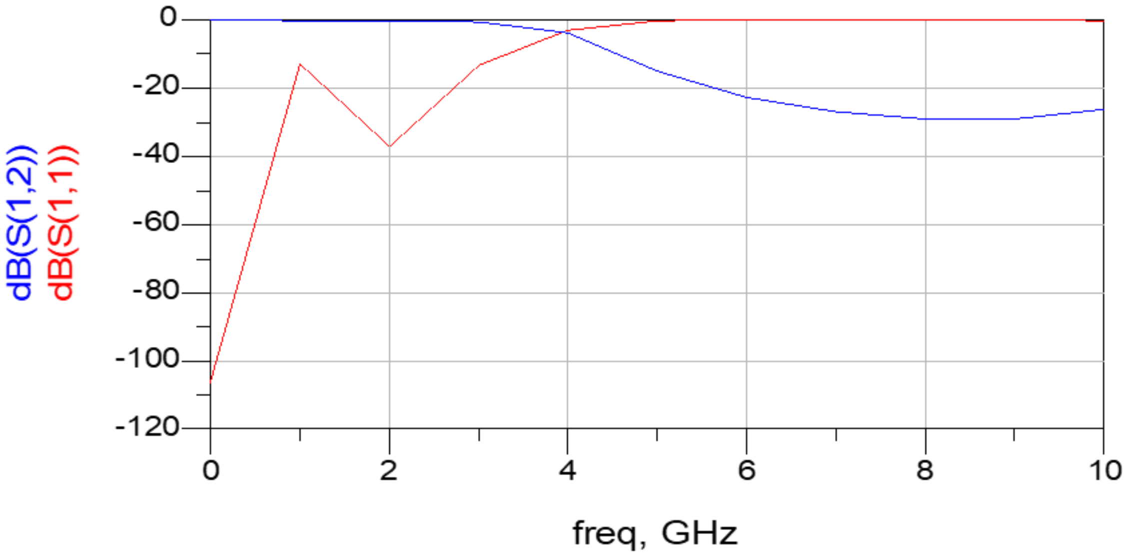


Fig. 23: The characteristic of the distributed transmission line showing variation of both incident wave and the forward gain with frequency.

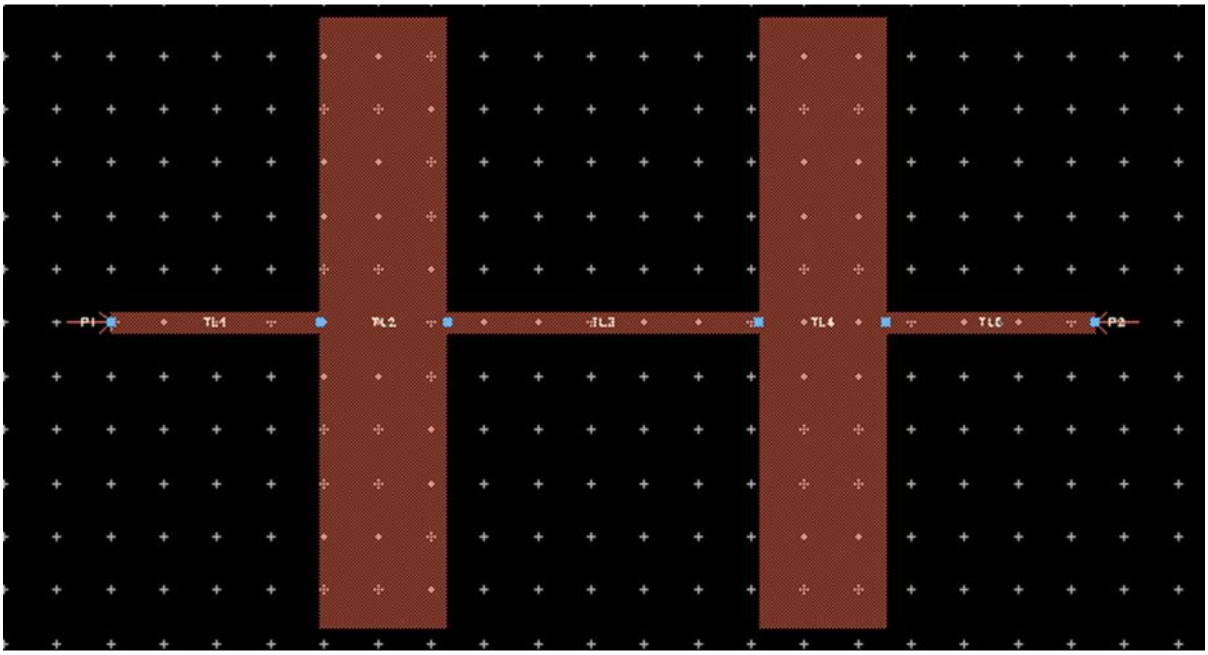


Fig. 24: The microstrip filter structure for the Chebyshev Low-Pass Filter.

The frequency response of Figure 11 shows that the maximally flat filter has a wide roll-off and there was a distortion at the passband at 1.5 GHz of -40 dB but in Figure 18 the distortion occurs at similar frequency at the -20 dB point. The design specification was met as a cut-off frequency of 4 GHz was achieved. The Chebyshev filter provides a slightly faster roll-off in the transition band (Figure 11 and Figure 18). Comparing Figure 13 and 23 it is apparent that the $S(1\ 2)$ attenuates at high frequency. The chebyshev experiences greater attenuation at high frequency. In order to resolve this problem a higher order should be used at high frequency.

5. Conclusion

In this paper, a stepped impedance microstrip low-pass filter for maximally flat filter with order $N = 7$ and Chebyshev filter with order $N = 5$ was simulated using ADS software. The frequency response of the maximally flat filter shows that it has a wide roll-off and there was a distortion at the passband at 1.5 GHz of -40 dB but in the distributed circuit the distortion occurs at similar frequency at the -20 dB point. The design specification was met as a cut-off frequency of 4 GHz was achieved. The Chebyshev filter provides a slightly faster roll-off in the transition band. Comparing Figure 13 and 23 it is apparent that the $S(1\ 2)$ attenuates at high frequency. The chebyshev experiences greater attenuation at high frequency. In order to resolve this problem a higher order should be used at high frequency.

Design and implementation of microwave filters can be done in several ways and differs in applications. For frequency multiplexing in satellite communication systems, waveguide cavity bandpass filters with very low insertion losses are recommended. For compatibility and cost, coaxial low-pass filters, designed with sections of coaxial line with varying diameters are cheap. Planar filters come in microstrip or stripline form and are valuable for integration with hybrid or monolithic microwave integrated circuits. The use of computer aided design (CAD) procedures in the building of sophisticated amplitude and phase responses, and field effect transistors (FET) for fabrication of active microwave devices helps to develop filters with tunable and gain responses.

References

1. [1] D. M. Pozar, “Microwave Engineering”, Fourth Edition, Wiley and Sons, 2012.
2. [2] Rajasekaran, K., J. Jayalakshmi, and T. Jayasankar. "Design and analysis of stepped impedance microstrip low pass filter using ADS simulation tool for wireless applications." International Journal of Scientific and Research Publications 3, no. 8 (2013): 1-5.
3. [3] Bohra, Hussain, and Amrit Ghosh. "Design and Analysis of Microstrip Low Pass and Bandstop Filters." International Journal of Recent Technology and Engineering (IJRTE) 8, no. 3 (2019): 6944-6951.
4. [4] J. S. Hong, “Microstrip Filters for RF Microwave Applications” John Wiley and Sons, 2011.
5. [5] Reinhold. Ludwig, Pavel. Bretchko, “RF Circuit Design: Theory and Applications”, Publishing House of Electronics Industry, pp.147-153,169-173, 2004.
6. [6] S. N. Taib, M. A. Othman, W.N.A. Makhzan, T. S. M. Arshad, N. Y. M. Yasin, M. M. Ismail, M. H. Misran, “An Analysis of Low Pass Filter Using Bowtie Defected Ground Structure (DGS) at 10 GHz for Radar Application”, 3rd International Conference on Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BM E) Bandung, November 7-8, 2013.
7. [7] Md. Nurunnabi Mollah, Md. Foisal Hossain, Jeffrey Shiang Fu, Dong-Hua Yang, “Novel Technique of Developing Microstrip Low Pass Filter (LPF)”, ICICS 2007.
8. [8] Ahmed Boutejdar, Abbas Omar, Anatoliy Batmanov, Edmund Burte, “New Low-Pass Filter Design Using Compensated Microstrip Capacitor and Coupled Meander Defected Ground Structure (DGS)”, IEEE 2008.
9. [9] Mohd Faizul bin MdIdros, Siti Farishabt Abu Hassan, “A Design of Butterworth Low Pass Filter’s Layout Based on the Effect of Filter’s Order on the Ideal Filter Approximation”, Symposium on Industrial

Electronics and Applications (ISIEA 2009), October 4-6, 2009, Kuala Lumpur, Malaysia, IEEE 2009.

10. [10] Karimi, Gholamreza, Ali Lalbakhsh, Khatereh Dehghani, and Hesam Siahkamari. "Analysis of novel approach to design of ultra-wide stopband microstrip low-pass filter using modified u-shaped resonator." ETRI Journal 37, no. 5 (2015): 945-950.
11. [11] Hayati, Mohsen, Farzin Shama, and Hamed Abbasi. "Compact microstrip lowpass filter with wide stopband and sharp roll-off using tapered resonator." International Journal of Electronics 100, no. 12 (2013): 1751-1759.
12. [12] Moloudian, Gholamhosein, Massoud Dousti, and Asghar Ebrahimi. "Design and fabrication of a compact microstrip low-pass filter with ultra-wide stopband and sharp roll-off-rate." Journal of Electromagnetic Waves and applications 32, no. 6 (2018): 713-725.
13. [13] Srivastava, Shreyasi, R. K. Manjunath, and P. Shanthi. "Design, simulation and fabrication of a microstrip bandpass filter." International Journal of Science and Engineering Applications 3, no. 5 (2014): 154-158.
14. [14] Jubril, Akinwande, and Dominic S. Nyitamen. "2GHz microstrip low pass filter design with open-circuited stub." IOSR-Journal of Electronics and Communication Engineering 13, no. 2 (2018): 1-9.
15. [15] Salama, S., Y. Battah, and A. Abuelhaija. "Stepped Impedance 7th order Maximally Flat Low Pass Filter Using Microstrip Line for X-Band Applications." In Journal of Physics: Conference Series, vol. 1803, no. 1, p. 012005. IOP Publishing, 2021.