Stepped Impedance Microstrip Lowpass Filter Design using Advanced Design Systems

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Abstract- This paper describes an advanced design systems (ADS) approach of stepped impedance microstrip low pass filter design for maximally flat or Butterworth responses. The cut-off frequency is 4 GHz with source and load impedances of 50 Ω. The insertion loss at passband is $0.5\ dB$ and stopband is $20\ dB$. In this filter design, an order $N = 7$ 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. 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 maximally flat filter characteristics. The plots show variation of incident wave $S(1,1)$ and forward gain $S(1,2)$ with frequency in GHz.

Index Terms- Stepped impedance, Lowpass filter, Microstrip, Advanced design systems.

I. INTRODUCTION

The control of frequency response at a certain point in a radio frequency (RF) or microwave system is implemented by a filter as a two-port network by providing transmission at frequencies within the passband of the filter and attenuation in the stopband of the filter. Band reject characteristics, bandpass, low-pass, and high-pass are typical filter responses. Microwave filters have applications in almost any class of RF or microwave communication, radar, or test and measurement system [1]. Filter theory and practice was developed in the early years before World War II by researchers such as Mason, Darlington, Sykes, Fano, Lawson and Richards. In the late 1930s, the image parameter method of filter design was developed and became prominent for low frequency filters in telephony and radio. Microwave filter and coupler development became very popular in the early 1950s due to contributions from a research group at Stanford Research Institute. Today, cutting-edge and state of the art computer-aided design (CAD) packages based on insertion loss method are used in microwave filter design. Microwave filter design remains an active area of research due to incessant growth and advances in network synthesis with distributed elements, deployment of low-cost temperature semiconductors and other materials, and the connection of active devices in filter circuits [1]-[2].

Filter theory and design have frequency characteristics with periodic structures, which comprised of a transmission line or waveguide periodically loaded with reactive elements. Periodic structures are of interest in filter design for their use in slow-wave components and travelling wave design, and also as they display basic passband-stopband responses that give rise to the image parameter method of filter design. 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. High-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 their 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. 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 $6\ GHz$.

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

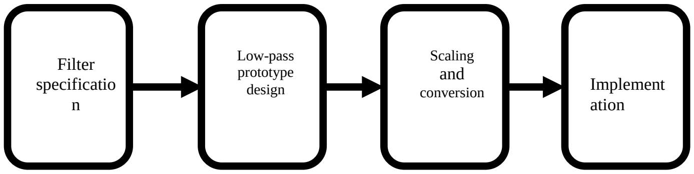

Figure 1. Filter design procedure by insertion loss method

A. 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:

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

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

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

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

$$N \geq 5.82. \qquad (.4)$$

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	0.445	1.247	1.802	2.0	1.802	1.247	0.445	1.0

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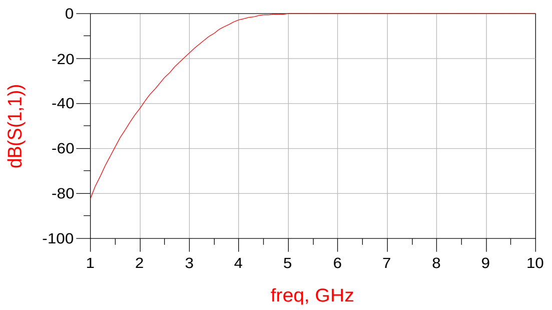


Figure 2. The characteristic of the microwave filter showing variation of incident wave with frequency

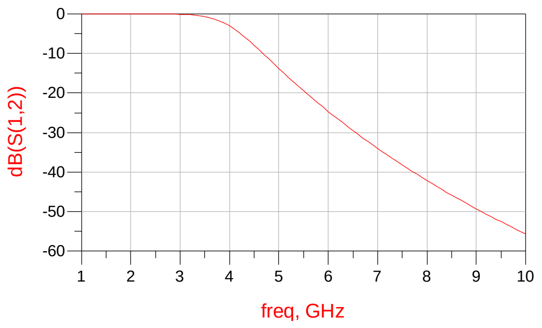


Figure 3. The characteristic of the microwave filter showing variation of the forward gain with frequency

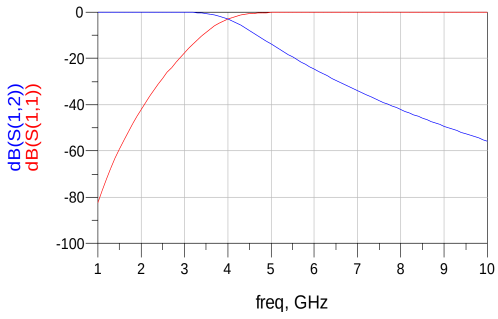


Figure 4. The characteristic of the microwave filter showing variation of both incident wave and the forward gain with frequency

The figures above illustrate 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 2 and figure 4 the cut-off frequency of 4 GHz was obtained.

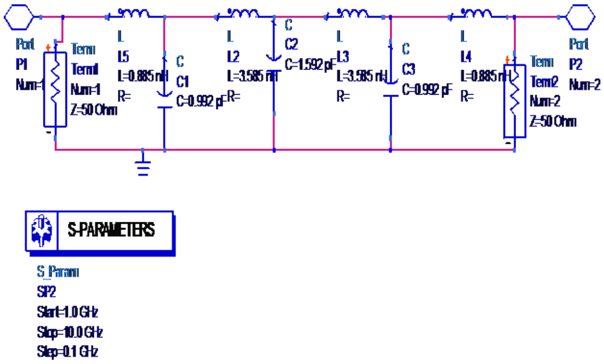
B. Design of Microwave Filter Prototype (L and C Elements) Scaled for the Given Frequency Band and 50Ω Input and Output Impedance.

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 $R_O = 50\Omega$,

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

Figure 5. Lumped circuit for maximally flat low-pass filter prototype obtained from ADS software.



C. 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. Shows distributed network parameters.

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

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.

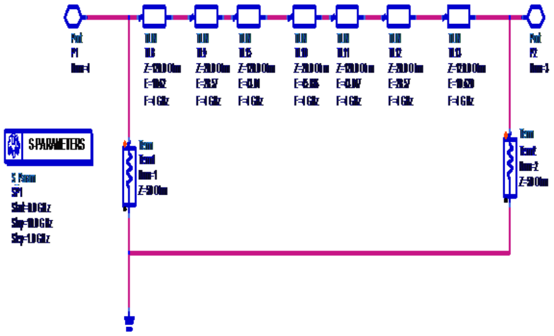


Figure 6. ADS representation of the distributed transmission line circuit

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 4 GHz which proves the fact that the design specification was achieved. The frequency responses of s_{12} and s_{21} are shown below.

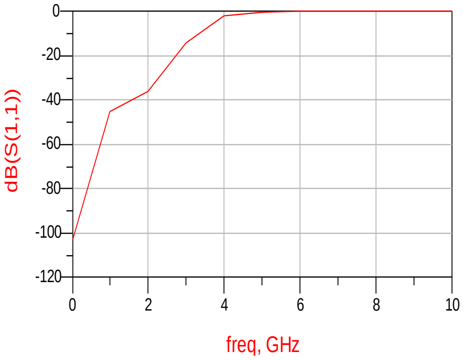


Figure 7. The characteristic of distributed transmission line showing variation of incident wave with frequency

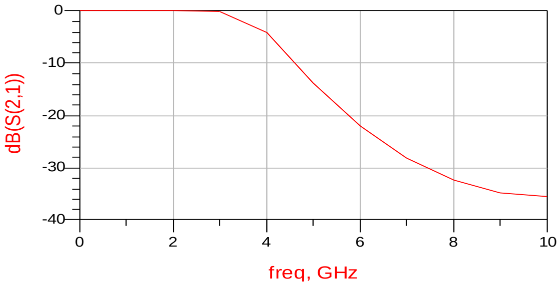


Figure 8. The characteristic of distributed transmission line showing variation of reversed gain with frequency

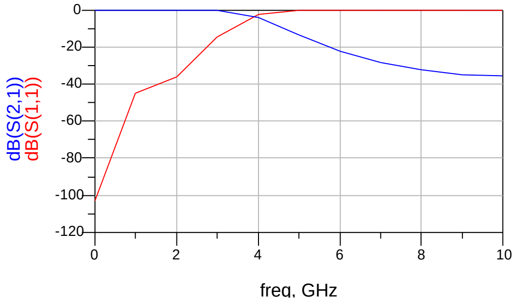


Figure 9. The characteristic of the distributed transmission line showing variation of both incident wave and the reversed gain with frequency

III. RESULTS AND DISCUSIONS

D. 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;

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

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

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

Table 4. Shows Distributed Parameters of Microstrip Maximally Flat low-pass filter.

Distributed component	Impedance scale	Electrical-length $(\beta l) in\ degrees$	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.

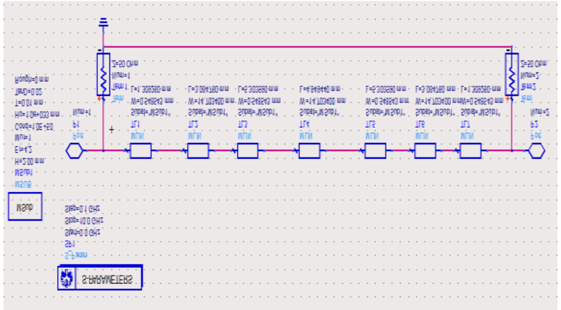


Figure 10. After simulating the ADS the following characteristics of the microstrip were obtained and the microstrip layout was obtained.

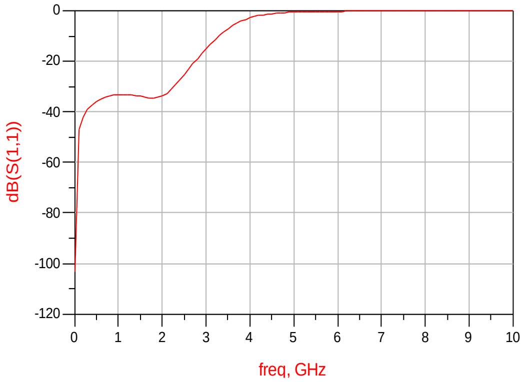


Figure 11. The characteristic of microstrip structure showing variation of incident wave with frequency

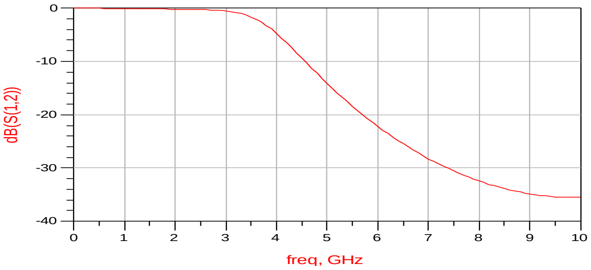


Figure 12. The characteristic of microstrip structure showing variation of reversed gain with frequency

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.

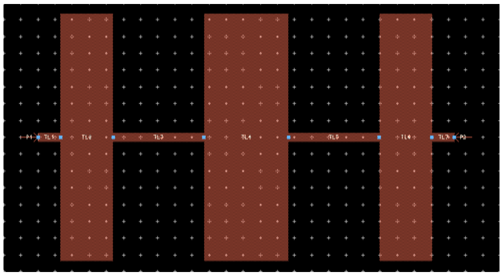


Figure 13. The microstrip filter structure for the maximally flat filter.

The frequency response of Figure 7 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. The design specification was met as a cut-off frequency of 4 GHz was achieved.

IV. CONCLUSION

Stepped impedance microstrip low-pass filter for maximally flat filter with order $N = 7$ 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. attenuation at high frequency. In order to resolve this problem a higher order should be used at high frequency.

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