Stepped Impedance 7th order Maximally Flat Low Pass Filter Using Microstrip Line for X-Band Applications

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Abstract. In this paper stepped impedance 7th order maximally flat low pass filter is designed and analyzed for X-band range at 9 GHz cut-off frequency. The filter is printed on Alumni substrate of dielectric constant 9.6 and thickness of 1.6 mm. The obtained attenuation is more than 20 dB. The Advanced Design System (ADS) software is used to design and simulate the proposed low pass filter. In addition, a comparison between filter design using insertion loss method implemented in stubs and stepped impedance is presented and discussed.

1. Introduction
Microwave filters are components which give frequency selectivity in several communication systems working at microwave frequencies. Microwave low pass filters attenuate the unwanted signals above the cut-off frequency. Because low pass filters are simple to fabricate, have compact size and low insertion loss, they are recommended in several applications such as cellular communications and microwave circuits. For stepped impedance filter design high and low impedances are used. Stepped impedance low pass filters utilize a cascaded structure of alternating high- and low-impedance microstrip transmission lines. Due to light weight, planar structure, low cost, compact size, and easy fabrication, microstrip technology in microwave filters design is preferred. In addition, microstrip transmission lines can be integrated simply to other components on a printed circuit board [1]. In [2], a stepped impedance 6th order low pass filter was designed for C-band applications. The filter was printed on FR4 substrate with a relative permittivity of 4.2 and thickness of 62 mil. The proposed microwave low pass filter used Butterworth approximation over 4 GHz frequency bandwidth and -20 dB attenuation at 6 GHz in stop band. In [3], a stepped impedance 6th order low pass filter was designed and implemented for S-band [2-4 GHz]. To get maximally flat response, Butterworth approximation was assumed. The design and simulation of the filter was performed using AWR microwave office simulation software. Measured results of the proposed filter showed that frequencies above 2.2 GHz are rejected. While in [4], a 3rd order Chebyshev stepped impedance low pass filter at 2.4 GHz was presented. Filter design and simulation was carried out using CST software. In [5] different order stepped impedance Chebyshev low pass filter at 5 GHz had been designed. By changing the length or the width of the low and high impedance, desired characteristics were obtained. The filter was designed using Hyper lynx 3D EM software. In [6], an ultra-wideband (UWB) band
pass filter using stepped impedance stub-loaded resonator was introduced. The used substrate has a relative dielectric constant of 2.55 and a thickness of 0.8mm. The proposed UWB filter is fed with two interdigital parallel coupled lines. The pass band region of the proposed UWB filter is from 2.9 to 10.9 GHz providing more degrees of freedom to control the resonant frequencies. This advantage makes the resonator suitable for UWB band pass filter applications. In [7], a conventional folded stepped impedance resonator SIR was modified by adding an inner SIR stub connected to the high impedance line of the main resonator. The modified structure was used as the basic for a dual-band bandpass filters. The first band depends on the outer folded SIR, while the second band is affected by the presence of the inner stub. Two models of ultra wideband (UWB) bandpass filters using stepped impedance stub loaded microstrip resonator (SISLMR) were presented in [8]. The first model was built by loading a uniform 50 Ω transmission line with three symmetrical stepped impedance stubs separated by a quarter-wave length. The passband region extends from 3.1 to 10.6 GHz. In the second model, two spurline sections were created around the central stepped impedance stub to get a sharp notch band for suppressing the signals for 5 GHz WLAN applications. Stepped impedance resonator (SIR) was used in [9] to get a compact size short stub narrow bandpass filter on a low dielectric constant substrate. Quarter-wavelength short circuit stubs were suggested instead of open circuit half-wavelength stubs for additional size reduction of the bandpass filter. The proposed filter with an overall size of 22 × 8.7 mm² was printed on Teflon substrate of relative dielectric constant of 2.54. An UWB bandpass filter on a triple-mode resonator (TMR) using a stepped impedance short circuit stub was introduced in [10].

2. Filter Design Procedure
It is difficult to realize filters beyond 500 MHz using lumped elements because the physical dimensions of the filter become comparable to the wavelength which in turns causes different losses that degrade the performance of the circuit. Consequently, the lumped element filters should be converted into distributed element realizations [11]. To convert lumped elements into distributed elements, Richard’s transforms is used. At microwave frequencies, the distance between components is not negligible and to solve for such a problem, Kuroda’s identities are used for separating filter elements by inserting transmission line sections [12]. In [12], 7th order maximally flat microstrip low pass filter based on insertion loss method was introduced. For comparison, in this work a stepped impedance 7th order maximally flat low pass filter with the same specifications as in [12] is designed and simulated using ADS software. Stepped impedance low pass filters are relatively easy to implement by using very high and very low impedance lines. Let’s consider the T-section equivalent circuit of a short section of transmission line of length βl, Fig.1(a), as determined from conversion of the ABCD parameters to Z parameters to identify the individual elements. For high Z₀ and small the equivalent circuit becomes \( X_L = Z_0 \beta l \), Fig.1(b). For low Z₀ and small βl, the equivalent circuit becomes \( B_C = Y_0 \beta l \), Fig.1(c). So short sections of transmission line can be used to realize a lumped element low pass filter in transmission line format. To use this approximation, it is required to know the highest and lowest feasible transmission line impedances, \( Z_h \) and \( Z_l \). This means that the idea behind the stepped impedance method is to use alternating sections of very high and very low characteristic impedance lines cascaded to form a ladder. Series inductors of a low-pass prototype are replaced with high impedance line sections, while shunt capacitors are replaced with low impedance line sections. In the designing process, the ratio \( Z_h/Z_l \) should be as high as possible. The highest and lowest line impedances in this design are chosen to be 120 and 20 Ω respectively. The source impedance \( Z_0 = 50 \) Ω, and the filter order is chosen to be \( N = 7 \). The filter element values and corresponding \( L \) and \( C \) are summarized in Table 1. The filter is printed on Alumni substrate of dielectric constant 9.6 and thickness of 1.6 mm. Schematic
Figure 1: (a) T-section equivalent circuit of transmission line section $\beta l$ and $Z_o$, (b) the equivalent circuit for high $Z_o$ and small $\beta l$, and (c) the equivalent circuit for low $Z_o$ and small.

Figure 2: Schematic diagram of the 7th order maximally flat LPF using lumped elements in ADS.

Table 1: Element values and corresponding L and C for stepped impedance maximally flat low pass filter.

| Element values | Corresponding L and C | High and low impedances, $Z_l$ $Z_h$ |
|----------------|-----------------------|--------------------------------------|
| $g_1=0.445$    | $C_1$                 | $Z_l=20 \, \Omega$                   |
| $g_2=1.247$    | $L_2$                 | $Z_h=120 \, \Omega$                  |
| $g_3=1.8019$   | $C_3$                 | $Z_l=20 \, \Omega$                   |
| $g_4=2.0$      | $C_4$                 | $Z_h=120 \, \Omega$                  |
| $g_5=1.8019$   | $C_5$                 | $Z_l=20 \, \Omega$                   |
| $g_6=1.247$    | $C_6$                 | $Z_h=120 \, \Omega$                  |
| $g_7=0.445$    | $C_7$                 | $Z_l=20 \, \Omega$                   |

diagram of 7th order maximally flat LPF is shown in Fig.2. In stepped impedance method, the capacitors and inductors are converted to $Z_l=20 \, \Omega$ and $Z_h=120 \, \Omega$ microstrip transmission line sections respectively. For each microstrip line section there will be a corresponding length $l_i$, $(i = 1, 2, \ldots, 7)$. For the microstrip line width, there will $W_{20\,\Omega}$ for low impedance section and $W_{120\,\Omega}$ for high impedance section as shown in Fig.3. The electrical length of the microstrip line section corresponding to capacitor $C$ is calculated as:
Figure 3: Stepped impedance implementation of the 7th order maximally flat LPF.

Figure 4: Schematic diagram of the stepped impedance 7th order maximally flat LPF using microstrip line sections in ADS.

\[
\beta l = \frac{C Z_i}{Z_o} \quad (1)
\]

and for inductor \( L \) the electrical length is calculated as:

\[
\beta l = \frac{L Z_o}{Z_h} \quad (2)
\]

To solve for the length of the microstrip line section corresponding to the capacitance \( C_i \), \( i = 1,2,\ldots,7 \)

\[
l_i = \frac{C_i Z_i}{\beta Z_o} \quad (3)
\]

While the length of the microstrip line section corresponding to the inductance \( L_i \), \( i = 1,2,\ldots,7 \)
can be calculated as

\[
l_i = \frac{L_i Z_o}{\beta Z_h} \quad (4)
\]

The length and width for each microstrip line section are calculated and summarized in Table 2.
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(a) (b)

Figure 5: Simulated scattering parameters of the LPF realized in Fig.2. (a) S11, and (b) S12.

| Microstrip line impedance | Electrical length $\beta l$ | Wavelength $\lambda$ (mm) | Microstrip line length $l$ (mm) | Microstrip line width $W$ (mm) |
|---------------------------|-----------------------------|---------------------------|-------------------------------|-------------------------------|
| 20 $\Omega$              | 10.20°                      | 10.95                     | 0.31                          | 6.89                          |
| 120 $\Omega$             | 29.77°                      | 12.66                     | 1.05                          | 0.11                          |
| 20 $\Omega$              | 41.30°                      | 10.95                     | 1.26                          | 6.89                          |
| 120 $\Omega$             | 47.75°                      | 12.66                     | 1.68                          | 0.11                          |
| 20 $\Omega$              | 41.30°                      | 10.95                     | 1.26                          | 6.89                          |
| 120 $\Omega$             | 29.77°                      | 12.66                     | 1.05                          | 0.11                          |
| 20 $\Omega$              | 10.20°                      | 10.95                     | 0.31                          | 6.89                          |

3. Simulation Results and Analysis

Stepped impedance 7th order maximally flat LPF is modelled in ADS using microstrip line sections, Fig.4. Each microstrip line section is modelled based on the corresponding length and width as calculated in Table 2. The scattering parameters of the filter are simulated in ADS and shown in Fig.5. It is clear from the figure that the cut-off frequency is at 9 GHz and the stop band attenuation is more than 20dB.

The filter layout is shown in Fig.6 and the corresponding scattering parameters are shown in Fig.7. The scattering parameters obtained from the filter layout realization are more accurate. It is clear from Fig.7 that the cut-off frequency is at 6 GHz. The coupling effect between microstrip line sections in this case is considered. This effect explains the difference between the scattering parameters obtained from the schematic and layout realization. Due to coupling effect, the cut-off frequency is reduced to 6 GHz. In addition, distortion in stop band region becomes clear.

In [12], a 7th order maximally flat lowpass filter using insertion loss method (stub realization) was designed and analyzed with the same specifications as the stepped impedance 7th order maximally flat low pass filter in this work. For comparison between filter design using stubs and stepped impedance method, the scattering parameters for both methods obtained from the schematic and layout realization are presented in Fig.8 and Fig.9 respectively. From schematic
results, the cut-off frequency of the filter implemented using stubs occurs at 5 GHz, while it occurs at 9 GHz for the stepped impedance realization. From layout results, the cut-off frequency becomes at 4 GHz and at 6 GHz for the stubs and stepped impedance respectively. In addition, stubs implementation shows more distortion in stop band region than stepped impedance implementation. In stubs realization, the number of stubs increases in proportion to the filter order, Fig.10, leads to higher coupling effect compared to stepped impedance realization.

4. Conclusion
In this work a stepped impedance 7th order maximally flat low pass filter is designed and simulated using ADS software. The proposed filter works for X-band range at 9GHz cut-off
frequency and an attenuation of more than 20dB is obtained. Due to coupling effect between microstrip line sections in the layout realization of the filter, the cut-off frequency becomes at 6GHz and distortion effect in the stop band region is seen. The scattering parameters of the same filter specifications in stubs and stepped impedance implementation are compared. Results show that wider pass band region is obtained from stepped impedance realization. In addition, stubs realization leads to higher coupling effect and more distortion in stop band region in comparison with stepped impedance realization.

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