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Design of a Low Cost Compact Elliptic Function LPF Using Open Circuited Stubs

Sarbani Sen*, Tamasi Moyra

Department of Electronics and Communication Engineering, National Institute of Technology, Agartala 799046, West Tripura, India

Corresponding Author Email: sensarbani77@gmail.com

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ABSTRACT

A miniaturized microstrip lowpass filter with low insertion loss and wide attenuation band is presented in this study. The filter is designed using two open circuited stubs and six stepped impedance resonators aligned symmetrically. The insertion loss in the passband varies from -0.049 to -0.5 dB. The proposed lowpass filter has 3 dB cut-off frequency at 3 GHz and the stopband region is extended from 3.59 GHz to 14 GHz with an attenuation level of -15.5 dB. The roll-off factor for the proposed filter is 56 dB/GHz and the relative stopband suppression achieved is up to 130 %. Hence, the presented filter structure operating in S-band can be used in multiple applications like radar, WiMAX and other RF devices.

1. INTRODUCTION

In RF and microwave communication, lowpass filters those have the features of compact size, sharp roll off and wide attenuation band are in high demand [1-2]. Such high-performance devices are commonly used in mixers, amplifiers and oscillators to block unwanted high frequency harmonics. The popular technique to design a microstrip lowpass filter (LPF) is the use of stepped impedance lines or high-low impedance lines [3-5]. These commonly used techniques provide poor cut-off response, very low rejection level of insertion loss (IL) and narrow stop band. Usually, there are two significant steps to design a conventional microstrip LPF, first one is selecting an appropriate lowpass prototype and the other is finding a microstrip realization [6-7]. But such traditional structures offer gradual fall at -3dB cut-off and high insertion loss. To improve the sharpness, more sections should be cascaded which will increase the circuit size. Another way to enhance the performance of the conventional stub line filters is by replacing connected lines with slow wave resonators. Generally, modern microstrip lowpass filters are designed using either hairpin shape resonator or L-shape resonator [8-10]. But these resonators usually exhibit narrow stopband characteristics. To improve the attenuation band performance input/output feed lines can be cross coupled for introducing additional transmission zeroes. Inclusion of defected ground structures (DGS) in the circuit is another way of improving the stop band performance [11-12]. A sharp roll-off factor while maintaining a minimum insertion loss is an important parameter to implement any microwave filter [13-16]. In case of LPF using coupled lines [17], the capacitance of the coupled lines is too small and hence the finite attenuation poles cannot be located close to the passband. This results in gradual fall of cut off frequency response leading to a narrow attenuation band.

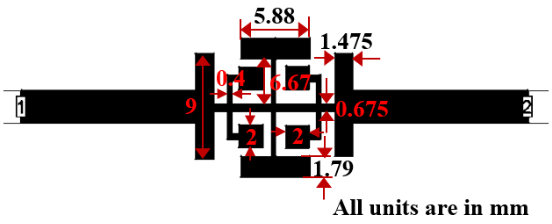
This work proposes a compact, low cost lowpass filter with low insertion loss and extended attenuation band. The filter prototype is modelled based on elliptic function response which provides infinite attenuation at finite frequencies. In order to obtain higher cut-off rate, the LPF is implemented using multiple open stubs which represent reactive elements. It is a generalized Chebyshev filter model of fourteen degree which introduces finite-frequency attenuation poles. The LPF is designed to have a cut-off frequency of 3 GHz and it possess minimum insertion loss of 0.049 dB and maximum insertion loss of 0.5 dB. The stopband suppression is up to -15.5 dB and it ranges up to 14 GHz. Hence, the obtained relative stop bandwidth (RSB) is 130 % with a suppression factor (SF) of 1.5. The roll factor is found to be 56 dB/GHz. In this study, the proposed microstrip LPF is designed and fabricated on FR4 substrate with a height (h) of 0.8 mm, a dielectric constant (ϵ_r) of 4.4, conductor thickness (t) of 0.04mm and loss tangent (δ) of 0.02. Eventually, the lumped equivalent circuit for the presented microstrip structure is proposed and the responses are compared accordingly. The LC values of the circuit are found by observing the attenuation poles and also optimized as per requirement. Finally, the EM simulated and measured responses are compared for experimental verification. There is a good agreement found between the predicted and measured results.

2. FILTER DESIGN

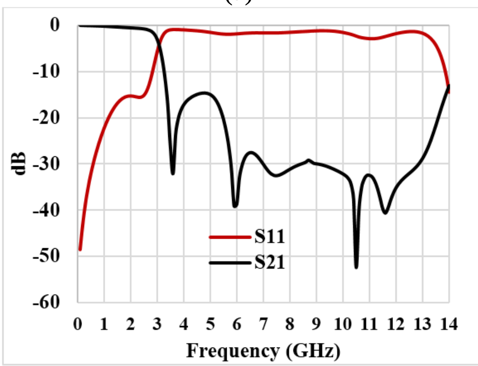
The design flow of the proposed lowpass filter structure begins with the microstrip realization followed by extraction of lumped equivalent circuit. Microstrip is chosen for the ease in fabrication.

2.1 Microstrip structure

Figure 1(a) shows the microstrip layout of the proposed lowpass filter. The filter comprises of two open-circuited stubs and six stepped impedance resonators parted by high impedance connecting lines. The physical lengths and widths of the presented structure is optimized to obtain the cut-off frequency at 3 GHz. Figure 1(b) shows the scattering parameters of the proposed LPF.



(a)



(b)

Figure 1. (a) Layout of proposed LPF (b) Scattering response of the filter

2.2 Comparison of conventional stepped impedance vs. proposed LPF

Figure 2(a) shows the conventional third order filter of 3 GHz cut-off frequency and Figure 2(b) depicts the comparison between the frequency responses of conventional LPF vs. proposed LPF. The conventional LPF suffers from gradual roll-off and poor attenuation band performance. To achieve sharp roll-off factor, the filter order should be increased. This will not only increase the circuit size but it will introduce additional insertion loss in the passband. To achieve high performance in smaller circuit area, the proposed LPF is designed. The physical lengths and widths of the conventional LPF can be obtained by using following formulas [7]:

$$l_{li} = \frac{\lambda_{gl} f_c}{2\Pi} Sin^{-1}(2\pi f_c \frac{L_i}{Z_{ol}}) \quad (1)$$

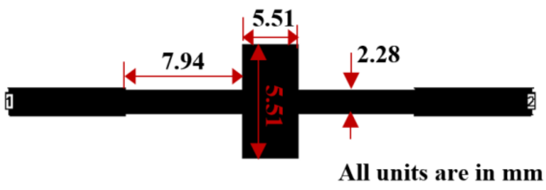
$$l_{ci} = \frac{\lambda_{gc} f_c}{2\Pi} Sin^{-1}(2\pi f_c Z_{oc} C_i) \quad (2)$$

where, λ_{gl} and λ_{gc} are the guided wavelengths of the hi-low lines, f_c is the cut-off frequency. L_i and C_i are the inductance and capacitance of the third order lowpass filter. It can be found by [7]:

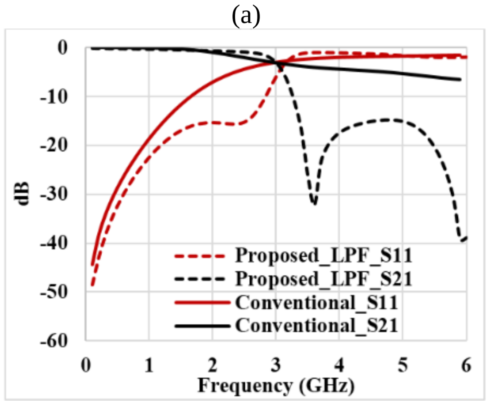
$$L_i = \frac{1}{2\pi f_c} Z_0 g_{li} \quad (3)$$

$$C_i = \frac{1}{2\pi f_c Z_0} g_{ci} \quad (4)$$

where, Z_0 = 50 Ω, g_{li} and g_{ci} denotes the inductive and capacitive elements [7]. Here, i = 1, 2, 3, 4, 5.



(a)

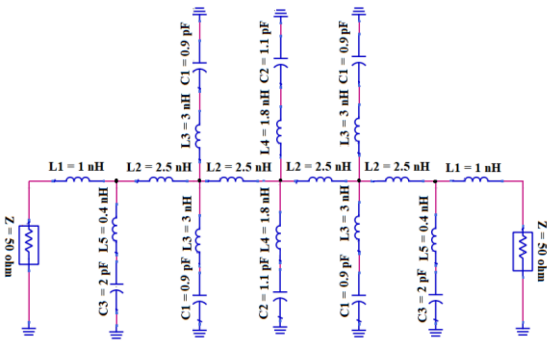


(b)

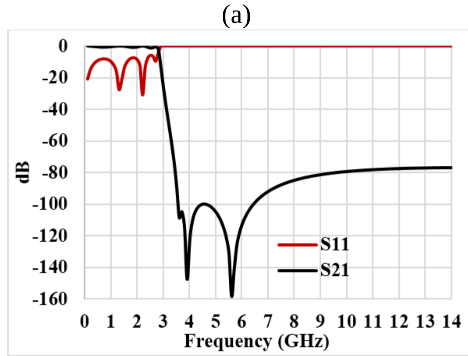
Figure 2. (a) Layout of conventional stepped impedance LPF (b) Frequency response of stepped impedance vs. proposed LPF

2.3 Equivalent circuit

The lumped equivalent circuit for the proposed lowpass filter can be obtained by using Eq. (3-4). Figure 3(a) shows the LC-equivalent circuit of the microstrip LPF and the frequency response is shown in Figure 3(b). The two-port network is terminated by 50 Ω impedance lines at either ends.



(a)



(b)

Figure 3. (a) Lumped equivalent circuit of the proposed LPF (b) Circuit simulated response

2.4 Current distribution

The current distribution with respect to frequency is shown in Figure 4. The current magnitude is highest at the cut-off frequency and lower at all other frequencies. It is observed that the LPF segments possesses more current at lower range of frequencies and gradually diminishes at the higher end (e.g. 7 GHz). This signifies that the structure is active at lower frequencies and the current flowing through the structure is unidirectional.

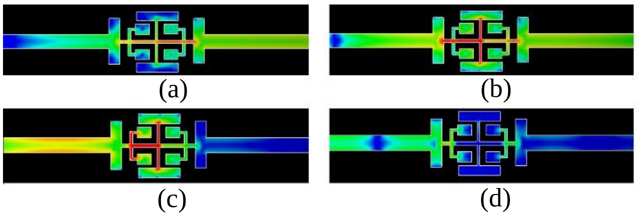


Figure 4. Current distribution at (a) 0.5 GHz (b) 2.4 GHz (c) 3 GHz and (d) 7 GHz

2.5 Filter characteristics

The proposed filter has the minimum insertion loss of -0.049 dB and maximum insertion loss of -0.5 dB. The roll-off factor can be obtained by:

$$\xi = \frac{\alpha_{max} - \alpha_{min}}{f_s - f_c} \quad \text{(dB/ GHz)} \tag{5}$$

where, α_{max} is the 40-dB attenuation point and α_{min} is the 3-dB attenuation point; f_s is the 40-dB stopband frequency and f_c is the 3 dB cut-off frequency. The calculated roll-off factor for the proposed LPF is 56 dB/GHz.

The relative stop bandwidth (RSB) is defined as:

$$RSB = \frac{StopBandwidth}{StopBandCenterFrequency} \tag{6}$$

It is found that the relative stop band suppression is achieved up to 130 % i.e. the RSB is 1.3. The suppression factor (SF), i.e. suppression/10 dB is found based on the average harmonic suppression in the stop band which is approximately 1.5. The normalised circuit size (NCS) is obtained by:

$$NCS = \frac{PhysicalSize(length \times width)}{\lambda_g^2} \tag{7}$$

where, λ_g is the guided wavelength at 3 dB cut-off frequency. The size of the proposed filter is (13.46 × 12.03) mm^2, which corresponds to $0.24\lambda_g \times 0.21\lambda_g$.

3. FABRICATION AND MEASUREMENT

The presented lowpass filter is fabricated and measured. The pictorial view of the fabricated structure is shown in Figure 5(a). The measured data vs. simulated data are plotted and shown in Figure 5(b). There is a good agreement obtained between the measured and simulated results. The proposed lowpass design has a wide attenuation band up to 14 GHz with a suppression level of -15.5 dB. It is fabricated using low cost FR4 substrate. Figure 5: (c) shows the group delay undergone by the LPF and it can be calculated as:

$$Group\ delay = -(\Delta \O)/\Delta\omega \quad \text{and } \omega = 2\pi f \tag{8}$$

where 'φ' is phase angle of S21 and 'ω' is the angular frequency whose unit is rad/sec.

It is projected that a filter should produce flattest group delay in the passband. The proposed LPF structure exhibits almost flat delay in the passband region. The average group delay in the passband is 0.00078 ns.

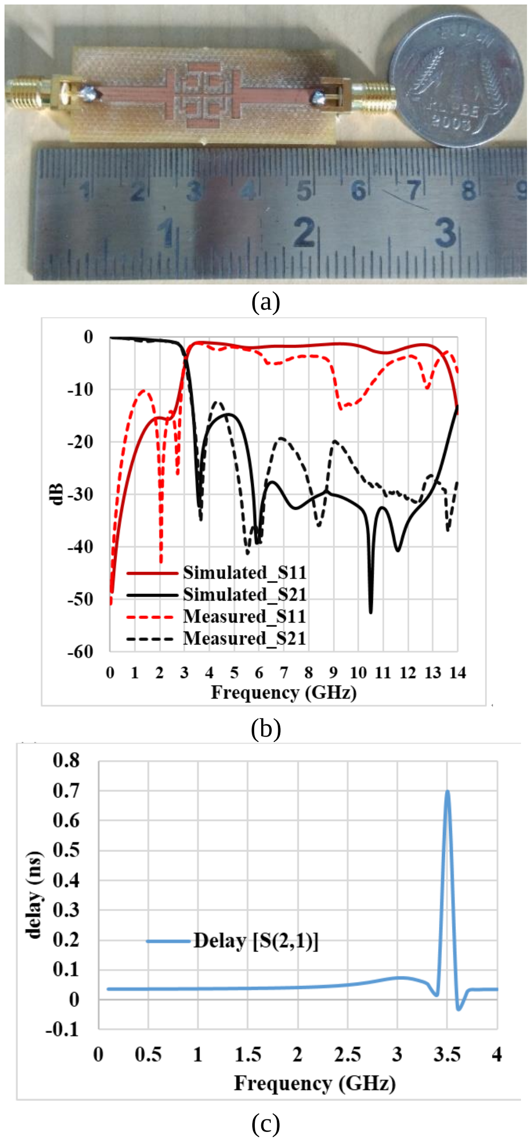


Figure 5. (a) Fabricated LPF structure (b) EM simulated response vs. measured response (c) Group delay

The performance comparison of the proposed work with the existing works are shown in Table 1.

The structures proposed in ref. [4] and ref. [14] are smaller in size but they exhibit poor stopband performance compared to the rest. An excellent attenuation band performance is achieved in ref. [15], but the roll-off (RO) factor is low. Similarly, the circuit recommended in ref. [5], exhibits poor roll-off, larger size and narrow stopband. The proposed filter is not only designed using cheap substrate material but also provides sharp roll-off and wider attenuation band.

Table 1. Comparative analysis of the proposed work with the existing work

Ref.	Dielectric material	f_c (GHz)	RO (dB/GHz)	Size ($\lambda_g \times \lambda_g$)	Stopband suppression
[4]	RT/Duroid 5880	1.5	36	0.037 × 0.093	-10 dB up to 15 GHz
[5]	FR4	2.4	36	0.35 × 0.2	-20 dB up to 6 GHz
[14]	Roger RO4003	0.85	23	0.089 × 0.081	-15 dB up to 12.6 GHz
[15]	RT/Duroid 5880	6	30	NA	-29 dB up to 60 GHz
This work	FR4	3	56	0.24 × 0.21	-15.5 dB up to 14 GHz

4. CONCLUSION

In this paper, a compact, low cost lowpass filter is proposed using open stubs and stepped impedance resonators. The LPF is designed to operate in S-band with a cut-off frequency of 3 GHz. Additional poles are generated by introducing the stepped impedance resonators. The structure is fabricated using low cost material and measured for experimental validation. The stopband suppression level of -15.5 dB is achieved up to 14 GHz and the maximum insertion loss in the passband is -0.5 dB. The performance of the filter can still be improved by using low loss substrate in the future. The stopband suppression is achieved up to fourth harmonic. With this good performance, the proposed lowpass filter can be used in various applications like RADAR, WiMAX and other communication systems.

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