

# Performance Evaluation and Optimization of Stepped Impedance and Stub-based Low-pass Filters for S-Band Applications

Naureen Butt, Ayesha Jaffar, Zeeshan Azmat Shaikh

**Abstract** — Wireless Communication is an integral part of modern communication systems. Microwave filters play a vital role in mobile and wireless communication systems. Microwave filters are used in most wireless communication systems having RF-front end for performing various signal processing tasks such as frequency selection, suppression of mixers unwanted intermodulation products etc. This paper presents the optimized design of low-cost microstrip technology based S-band low-pass filters using two different design topologies like: stepped impedance and stub-based filters. Low-pass filters of order  $N=5$  are designed, optimized and simulated using the ADS tool to achieve minimum insertion loss ( $S_{21}$ ) in pass-band and attenuation greater than 20dB at 3.5GHz. Consequently, optimized filters are manufactured and tested using Vector Network Analyzer (VNA) for  $S_{21}$  parameter of device under test (DUT) . Finally, comparison of post simulation and measured results are carried out for the proposed filters.

**Index Terms** - FR-4 substrate, Kuroda's identities, Microstrip low-pass filter, Richard's transforms, Stepped impedance

## I. INTRODUCTION

Wireless communication is nothing but transfer of useful data between two points in the absence of wired link. It's like a divine gift to mankind allowing users to be in ubiquitous connectivity anywhere in the world. One of the biggest challenge for wireless communication is to achieve carrier-wave communication, which catalyzes one's interest to explore wireless technology to meet the exploding demands of modern era. A lot of advancement has been made in radio frequency (RF) communication, which is one of the most common types of wireless communication. There is plethora of research ongoing to effectively utilize RF-spectrum using cost effective solutions without compromising on intended yield. The most prevailing demands of broader bandwidths, higher efficiencies in conjunction with lower cost, smaller and lighter products makes RF communication more appealing [1].

Filters remain an indispensable part of communication system since its inception. In RF communication, frequency-selective filters are required to pass and attenuate signals in specified frequency band. In this work, we focus on S-band low-pass filters that are basically converse of high-pass filters. The low-pass filter allows energy to the load at frequencies below the cut-off frequency with minimal insertion loss. But attenuation increases as substantial

amount of energy is bounced back to the source beyond cut-off frequency. The most popular filter responses are maximally flat (i.e Butterworth) and Chebyshev response. The maximally flat response signifies the ripple free response in pass-band. Whilst, the Chebyshev or equi-ripple filter response is far more superior to Butterworth response that is seldom used now a days [2]. The Chebyshev response gives rise to the steeper cut-off with equal ripples in pass-band. Low-pass filters find their optimum use in majority of millimeter-wave and microwave systems to facilitate the desired low frequencies below cut-off and they reject the higher frequencies.

The passive (LC) frequency-selective filter performs well up to a few hundred megahertz, but its performance deteriorates at higher frequencies [3]. Lumped element based filters are difficult to realize at high frequencies so they must be converted into distributed elements for practical realization [4]. Generally, low-pass filter synthesis with the help of insertion loss method is carried out in agreement with the steps mentioned as, 1) Design of filter prototype to have required pass-band characteristics. 2) Lumped element based low-pass filter prototype conversion to the desired filter type as per opted topologies. Therefore, impedance and frequency transformations are made for stepped impedance and stub loaded low-pass filters. 3) Practical design of filters. In this paper stepped impedance and open ended shunt stub-based filters are proposed. The complete design procedure of required topologies is given in Section II and V respectively. For the lowest cost, microstrip based circuits may be built on an ordinary FR-4 (standard PCB) substrate. FR-4 substrate is used for manufacturing purpose. Although different variants of transmission lines are available but microstrip-based realization of filters is preferred because of compact size, light weight, planar structure and ease of integration with different active or passive components over a single circuit board. Waveguide or coaxial based structures are used while dealing with high-power requirements. FR-4 is glass fabric-reinforced epoxy resin system with reduced burning rate while ratings FR-1 through FR-3 are paper-reinforced epoxy resin systems. There are other laminates systems too, which, are far more superior than FR-4 in terms of their electrical and mechanical characteristics [5]. As FR-4 is low cost commonly available resin-system therefore we opt for it in this research work. Filters are constructed using 62 mil thick FR-4 substrate with dielectric constant  $\epsilon_r = 4.4$ . The modern insertion loss method is used for filter designing and later on the results are validated using Full-wave analysis of ADS.

Our major contribution for both filter topologies is to have minimum insertion loss and fair amount of suppression for unwanted frequency components through optimization. To the best of our knowledge, for 5<sup>th</sup> order stepped impedance LPF our achieved attenuation in stop-band is higher than the existing results of 6<sup>th</sup> order LPF of Sudipta

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and Santhosh [6]. Therefore, our designed 5th order stepped impedance based low-pass filter provides better insertion loss in pass-band along with optimum level of attenuation that can be obtained using higher order LPF at 3.5GHz [4]. Generally, higher order filters are chosen to achieve steeper roll-off in transition band and achieve good suppression characteristics in stop-band. Application of Richard transformation and Kuroda's identity is one of the best means to cope with the requirements of reduced transition band and higher attenuation in stop-band without resorting to higher-order filters, thereby resulting in compact filters [7]. Thus, with the same filter specifications to attain better roll-off in transition band and to have substantial amount of attenuation than the former topology, we come up with the optimized version of loaded stub low-pass filter where we remain successful to achieve a large amount of attenuation at 3.5GHz that is much larger than the LPF topology mentioned earlier. Thus, our 5-pole filters can acquire aforementioned objectives in terms of insertion loss, roll-off and attenuation.

The remaining paper is organized as follows. Section II demonstrates the design methodology of stepped impedance LPF. The dimensions of this LPF are computed in Section III. Section IV comprises of simulated and measured results of the above said LPF. Section V describes the design procedure of stub loaded LPF. Shunt stub based filter fabrication and test results are shown in section VI. Finally, section VII concludes this paper

## II. DESIGN PROCEDURE OF LOW-PASS MICROSTRIP STEPPED IMPEDANCE FILTER

The modern insertion loss method is brought into play to synthesize a desired filter response, allowing control over the pass-band and stop-band amplitude and phase characteristic. Two major steps of filter designing are: selection of a suitable low-pass filter archetype, a kind of response with a certain level of pass-band ripples and order of the filter in agreement with filter specifications. The element values of the low-pass filter prototype are subjected to normalization to have generator impedance  $g_0=1$  and cut-off frequency ( $\omega_c$ )=1. Afterwards, they are altered to ladder-type circuit with source and load impedance of  $50\Omega$  for microstrip filters [8]. Element values for Nth order Chebyshev low-pass filter with a certain ripple level in pass band are enumerated from  $g_0$  at the source impedance to  $g_{N+1}$  at the load impedance.

The Filter Specifications are

1. Topology: Stepped impedance
2. Relative dielectric constant ( $\epsilon_r$ ) = 4.4
3. Thickness of substrate (h) = 62mil
4. Cut off frequency ( $f_c$ ) = 2.5GHz
5. The loss tangent ( $\tan\delta$ ) = 0.019
6. The system impedance  $Z_0 = 50\Omega$
7. The Highest practical line impedance  $Z_h = 120\Omega$
8. The lowest practical line impedance  $Z_l = 20\Omega$
9. Pass band ripple factor = 0.5 dB
10. Insertion loss ( $S_{21}$ )  $\geq 20$ dB at 3.5GHz

First step is to compute the order of filter satisfying the insertion loss specifications at 3.5 GHz. Figure 1 depicts that  $N=5$  is sufficient for at least 20 dB attenuation at 3.5 GHz with ripple level of 0.5 dB in pass band. Filter prototype element values for  $N=1$  to  $N=6$  are tabulated below [9]. So, Table I. gives element values such as

$$\begin{aligned} g_0 &= 1.00 \text{ (generator conductance)} \\ g_1 &= 1.7053 = L_1 \\ g_2 &= 1.2296 = C_2 \\ g_3 &= 2.5408 = L_2 \\ g_4 &= 1.2296 = C_3 \\ g_5 &= 1.7053 = L_4 \\ g_6 &= 1.00 \text{ (load conductance as } g_5 \text{ is a series inductor)} \end{aligned}$$

TABLE I. ELEMENT VALUES FOR EQUAL-RIPPLE LOW-PASS FILTER PROTOTYPES

N	0.5dB ripple						
	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$	$g_6$	$g_7$
1	0.6986	1.0000					
2	1.4029	0.7071	1.9841				
3	1.5963	1.0967	1.5963	1.0000			
4	1.6703	1.1926	2.3661	0.8419	1.9841		
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000	
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841

Low-pass Chebyshev filter prototype is presented in Fig. 2.

The electrical length ( $\theta = \beta l$ ) for inductors and capacitors for microstrip structure realization are calculated using (1) and (2) [8].

$$\beta l = \frac{LZ_0}{Z_h} \quad (\text{inductor}) \quad (1)$$

$$\beta l = \frac{CZ_0}{Z_l} \quad (\text{capacitor}) \quad (2)$$

The width (W) of the strip conductor is function of its characteristic impedance [14]. To compute the physical dimensions like Width (W) and length (l) corresponding to the electrical length of each inductor and capacitor section, we use following formulas [4].

$$\begin{aligned} \frac{W}{h} &= \frac{8e^A}{e^{2A-2}} \quad \text{if } \frac{W}{h} < 2 \\ &= \frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left\{ \ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right\} \right] \quad \text{if } \frac{W}{h} > 2 \end{aligned}$$

where

$$A = \frac{Z_0}{60} \sqrt{\frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{\epsilon_r + 1}} \left( 0.23 + \frac{0.11}{\epsilon_r} \right) \text{ and } B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}$$

Hereafter, using (3) the guided wavelength ( $\lambda_g$ ) helps to calculate the physical length (l) of each capacitive and inductive section of stepped impedance filter.

$$\lambda_g = \frac{\lambda}{\sqrt{\epsilon_e}} \quad (3)$$

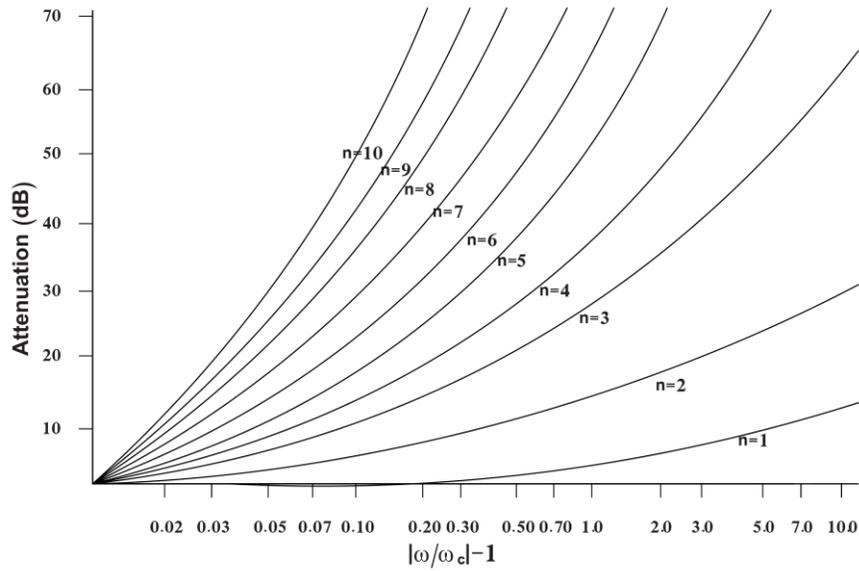


Fig.1 Attenuation versus normalized frequency for equi-ripple filter prototypes for 0.5dB ripple level [4]

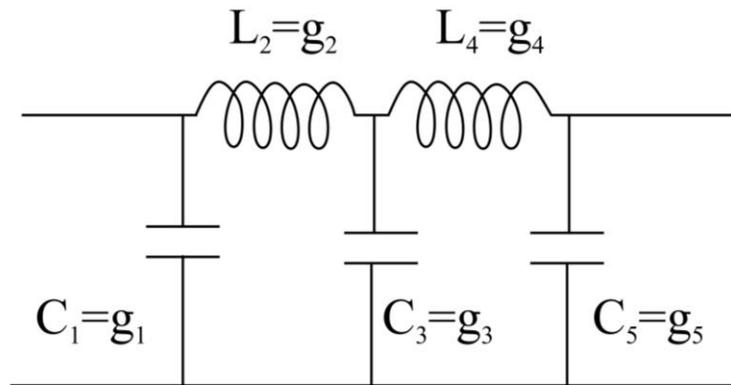


Fig. 2. Low-pass filter prototype circuit of order =5

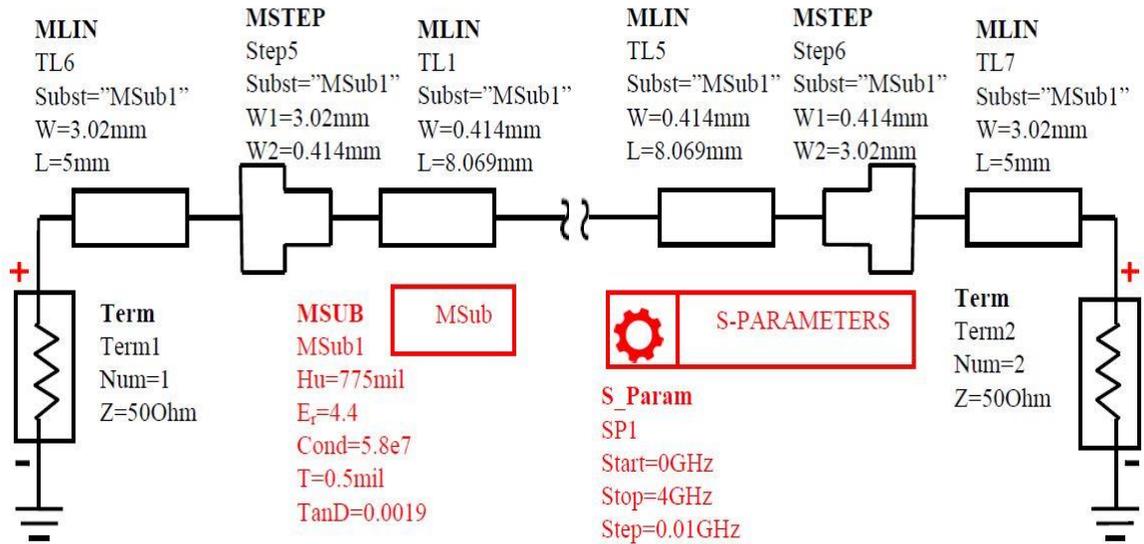


Fig. 3. Schematic of equi-ripple transmission line stepped impedance LPF

Where  $\lambda$  is operating signal wavelength and  $\epsilon_e$  is the effective dielectric constant. The effective dielectric constant can be found using (4)

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ \frac{1}{\sqrt{1 + 12 \frac{h}{W}}} \right] \quad (4)$$

TABLE II. PHYSICAL DIMENSIONS OF STEPPED IMPEDANCE FILTER OF ORDER (N) = 5

Section	$Z_l$ or $Z_h$	$\beta l_i$	$W_i$ (mm)	$l_i$ (mm)
1	120 $\Omega$	40.73 $^\circ$	0.414	8.069
2	20 $\Omega$	28.18 $^\circ$	11.341	4.093
3	120 $\Omega$	60.66 $^\circ$	0.414	12.015
4	20 $\Omega$	28.18 $^\circ$	11.341	4.093
5	120 $\Omega$	40.73 $^\circ$	0.414	8.069

In accordance with the above computed dimensions, the resultant circuit shown in Fig. 3 is simulated on ADS.

### III. SIMULATIONS AND MEASUREMENTS

Simulations are carried out to validate the designed circuitry. Figure 4 highlights LPF response, illustrating insertion loss variation versus frequency.

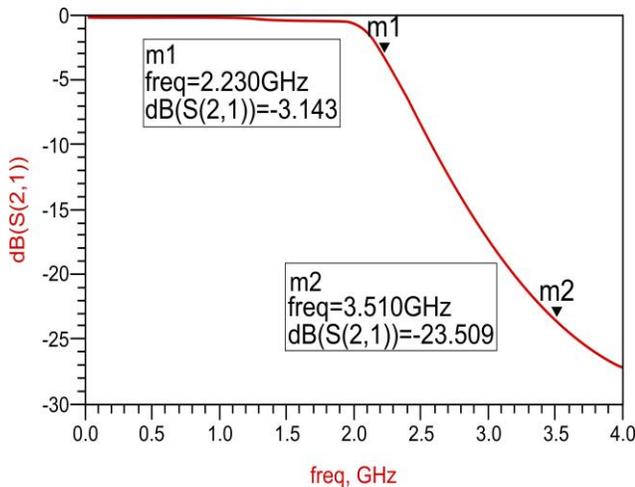


Fig. 4 Insertion loss ( $S_{21}$ ) of designed circuit vs frequency

Full wave EM analysis on ADS is carried out to generate more accurate results. As microstrip structure doesn't support pure transverse electric-magnetic (TEM) mode [10], therefore in order to satisfy boundary conditions, longitudinal components of electric and magnetic field must be taken into account. Furthermore, the indigenous momentum tool of ADS aids to account for hybrid modes which are generated due to superposition of Transverse Electric (TE) and Transverse Magnetic (TM) modes [11]. The Momentum layout and 3-D preview of the designed circuit are illustrated in Fig. 5(a) and Fig. 5 (b) respectively.

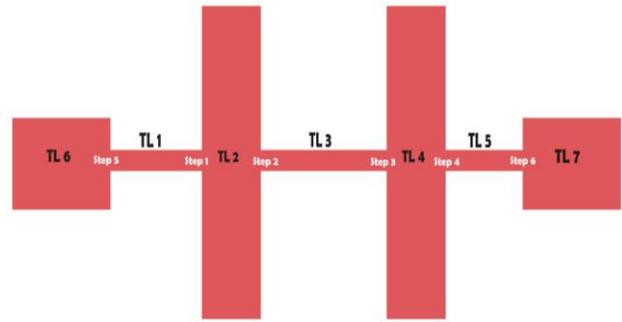


Fig. 5(a) Layout of LPF designed on FR-4 substrate ( $\epsilon_r = 4.4$ ) at cut-off frequency 2.5 GHz

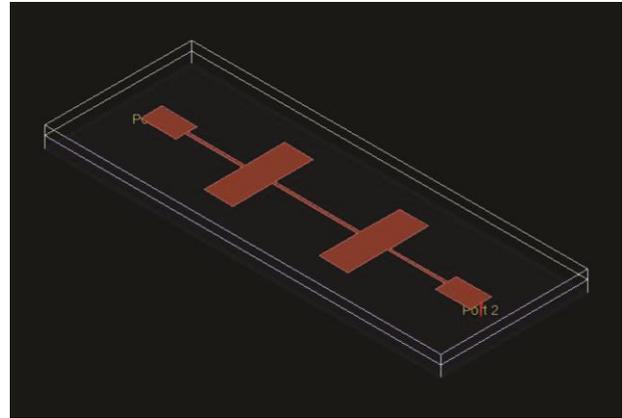


Fig. 5(b) 3-D preview in momentum

Momentum response of designed LPF is shown in Fig. 6

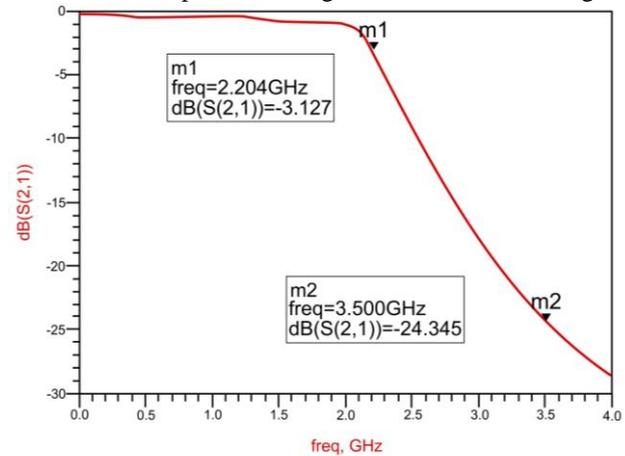


Fig. 6 Insertion loss ( $S_{21}$ ) vs frequency

In the wake of above simulated results, it is evident that designed filter is adequate for S-band applications as it can pass frequency components below 2.2GHz with minimum insertion loss and rejects the signal beyond 2.5GHz, with desired attenuation.

Photograph of manufactured filter is given in Fig. 7. Network Analyzer is used for performance measurements. Hence, measured  $S_{21}$  results shown in Fig. 8 are in close agreement with simulated ones. LPF following stepped impedance topology, find their way to front-end applications where one can compromise on sharp cut-off [12].

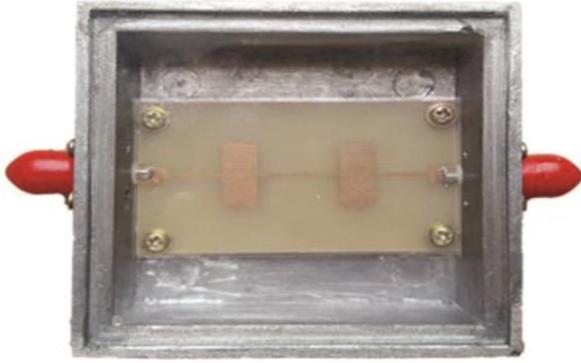


Fig. 7 Snapshot of fabricated LPF

Markers placement actually reflects response level at specific frequency. The VNA helps to do so as depicted in Fig. 8.

#### IV. STUB BASED LOW-PASS FILTER

Admittedly this filter design is based on standard design procedure using Richard’s transformation and Kuroda’s identities, however, our design is subsequently optimized using aforementioned Computer Aided Design (CAD) tool in order to achieve better roll-off and attenuation in transition-band and stop-band respectively.

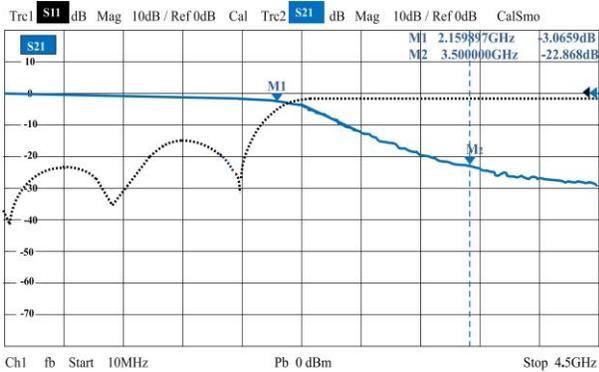


Fig. 8 Response of physically implemented filter

To get better transition and stop-band response of LPF few converts are made in form of open circuited stubs. The first step entails the selection of filter prototype as provided in Fig. 9. Meanwhile, normalized values of filter prototype (order = 5) are selected from Table I. such as  $g_1 = 1.7058$ ,  $g_2 = 1.2296$ ,  $g_3 = 2.5408$ ,  $g_4 = 1.2296$  and  $g_5 = 1.7058$ .

Then 5th degree filter is gone through “Richard’s Transformation” to employ  $\frac{\lambda}{8}$  long open or short circuited stubs, emulating capacitive and inductive attributes of lumped components respectively [13]. Equation (5) and (6) help to the above said stub’s synthesis [4].

$$jX_L = jL \tan \beta l \tag{5}$$

and

$$jB_C = C \tan \beta l \tag{6}$$

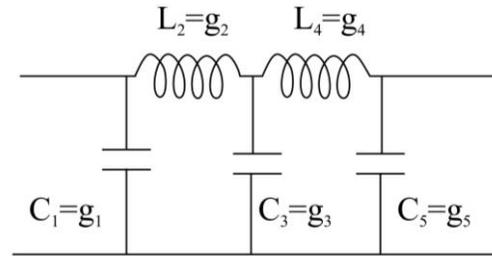


Fig. 9 Low pass filter (N = 5 ) prototype

Hence, transformed circuitry looks like Fig. 10. To get its more realistic design, Kuroda’s identities are applied to physically separate separate transmission line stubs introducing unit elements (i.e  $\frac{\lambda}{8}$  at  $\omega_c$  ). These separators (i.e unit elements) don’t affect filter response. Moreover, identities can alter series stubs into shunt stubs, seems to be more feasible for microstrip structure. So, in compliance with this objective, the two Kuroda’s identities whose equivalent circuits provided in Fig. 11 are applied to procure practical design.

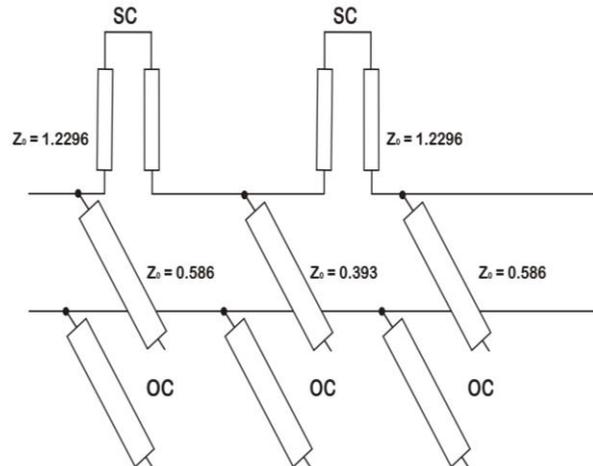


Fig. 10 Transfigured circuit

Afterwards, the addition of unit elements on input and output side of circuit of Fig. 10, following Kuroda’s identities explained in Fig. 11, finally yields the circuit provided in Fig. 12.

The Corresponding Width and physical length of each unit element and transmission line open circuited shunt stubs are enumerated in table III. These can be computed using line-Cal tool in ADS providing electrical length (i.e  $\theta = \frac{\lambda}{8}$  ), characteristic impedance ( $Z_0$ ) and designed frequency for the same substrate defined in the preceding section.

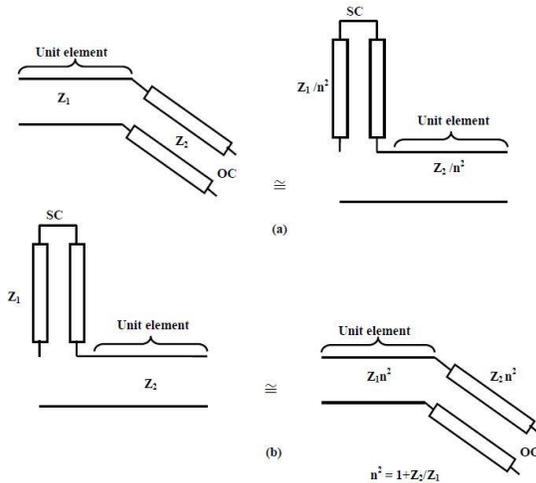


Fig. 11 Equivalent circuits defining Kuroda's Identities

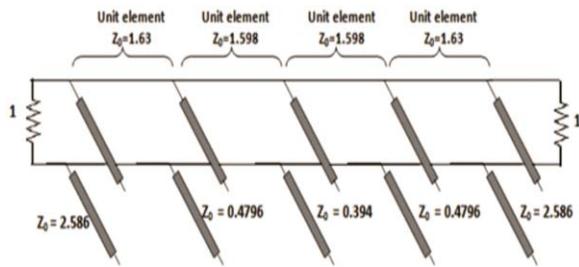


Fig. 12 Implementing Kuroda's identities

Finally, the above circuit undergoes impedance and frequency scaling and we are left with the circuit shown below.

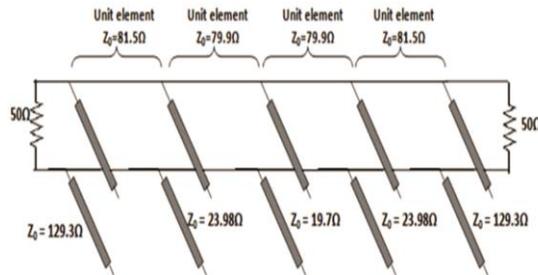


Fig. 13 Frequency and impedance scaled Circuit

Open circuited stub based Chebyshev LPF with 0.5 dB ripple factor designed in ADS as illustrated by schematic proposed in Fig. 14. Subsequently, simulation followed by optimization is performed, if needed.

Hence, Simulation is performed to confirm the intended output response of the designed stub based low-pass filter. Figure 15 illustrates the post simulation result, plotting insertion loss ( $S_{21}$ ) versus frequency.

Optimization is an indispensable procedure to instigate the optimum goals of the designed circuitry. In Fig. 16 optimization is done to conform the desired output of filter. The designer has to setup goals that are practically possible and one has to face no hassle to meet the targets.

The filter response after optimization gives much better

attenuation at 3.5 GHz compared with the pre optimization response. In Fig. 17 one may notice the better roll off with the good band rejection after 2.2 GHz.

Figure 18 portrays the momentum produced filter layout which facilitates while fabricating.

Full wave analysis of optimized filter gives filter response depicted in Fig. 19.

TABLE III. PHYSICAL DIMENSIONS OF UNIT ELEMENTS AND SHUNT STUBS FILTER OF ORDER (N) = 5

$Z_0$	$\theta$	$W(mm)$	$l(mm)$
50.00 $\Omega$	$\lambda/4$	3.023	16.405
129.3 $\Omega$	$\lambda/8$	0.297	8.802
81.50 $\Omega$	$\lambda/8$	1.160	8.526
23.98 $\Omega$	$\lambda/8$	8.765	7.779
79.91 $\Omega$	$\lambda/8$	1.215	8.513
19.70 $\Omega$	$\lambda/8$	11.243	7.686

### V. FABRICATION AND EXPERIMENTAL RESULTS OF STUB LOADED LOW-PASS FILTER

The loaded stub filter is fabricated on same substrate using microstrip technology. That is the best option for its several promising features like low cost, compact size, planar structure and light weight in comparison with other structures [3]. Finally, the manufactured filter shown in Fig. 20 is tested on VNA, yielding the response as given in Fig. 21.

In Fig. 21 one can notice a sharp roll-off with optimum level of attenuation at 3.5GHz. It is clear from the measured results that insertion loss is 0.670dB at 2.03 GHz, suppressing frequency components beyond 2.03GHz. These results are in accordance with momentum generated results. Hence, this filter can be used for S-band applications.

### VI. CONCLUSION

We proposed the optimized design of low-cost microstrip technology based S-band low-pass filters using two different design topologies (1) Stepped impedance (2) Stub-based filters. Specifically, designs of low-pass filters were optimized and simulated using the ADS tool to achieve minimum insertion loss ( $S_{21}$ ) in pass-band and attenuation greater than 20 dB at 3.5 GHz. Our optimized filters were then fabricated and tested using VNA in terms of  $S_{21}$  parameter of DUT. This work validated the design procedure of two optimized low-pass filters via simulation and fabrication. Measured results of both filters are in compliance with simulated results generated by CAD tool. Comparison of printed low-pass filters revealed that the stepped impedance low pass filter is readily applicable in wireless front-end applications where sharp transition is not mandatory. It is further observed in our designs that open circuited shunt stub loaded filter offered considerable improvement in transition and stop band regions.

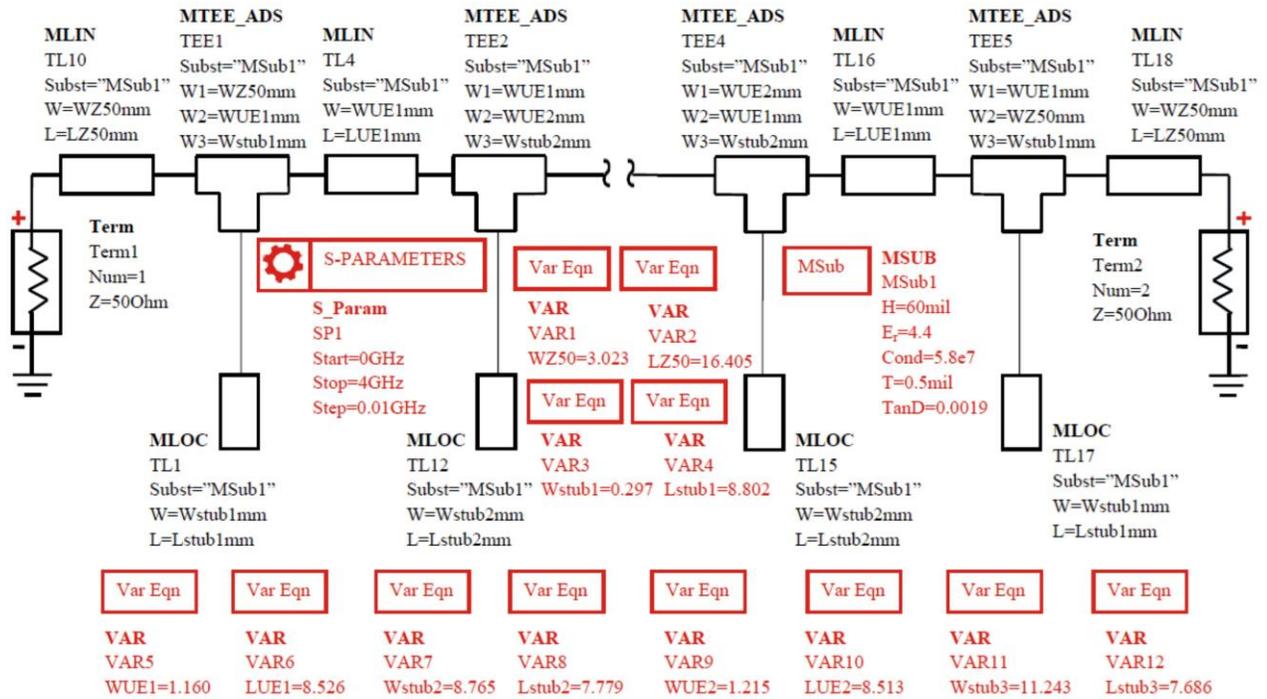


Fig. 14. ADS LPF schematic before optimization

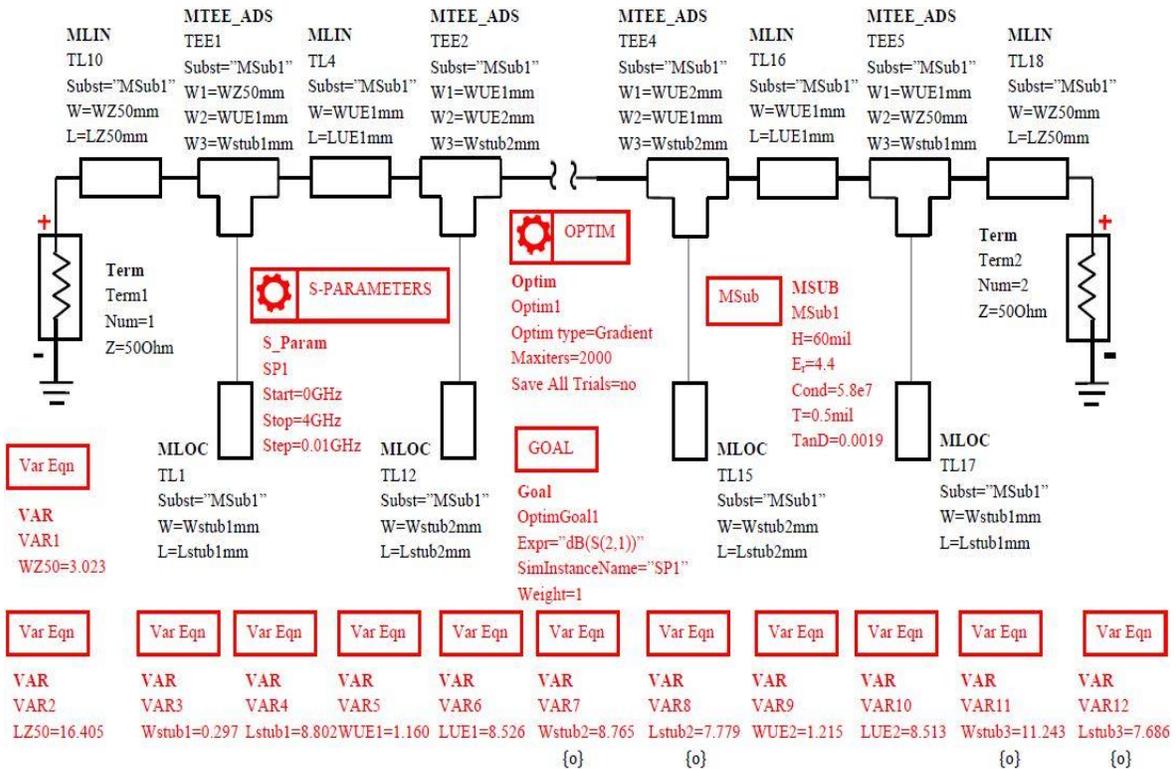


Fig. 16 Schematic with optimized filter dimensions

ACKNOWLEDGMENT

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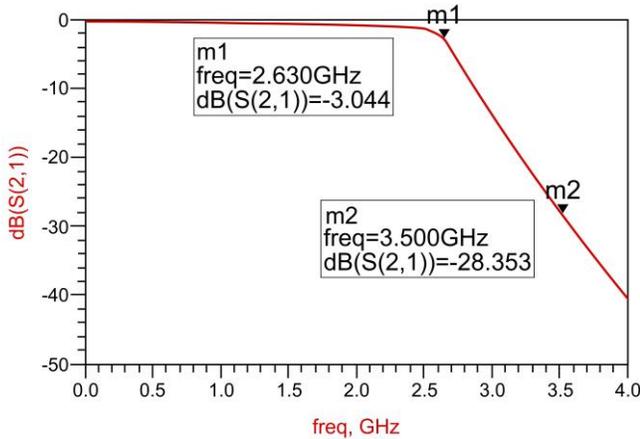


Fig. 15 Simulation result of stub based LPF

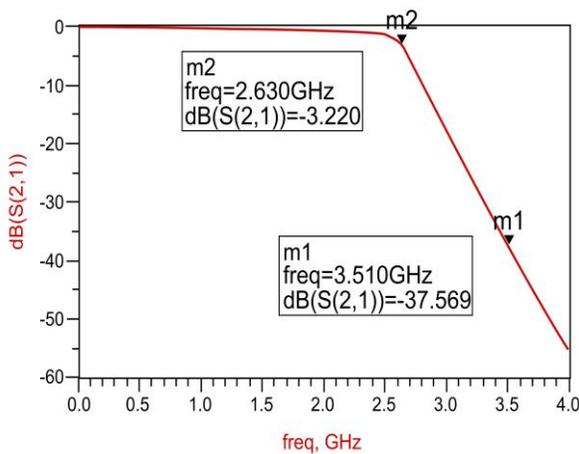


Fig. 17 Chebyshev stub loaded filter response after optimization

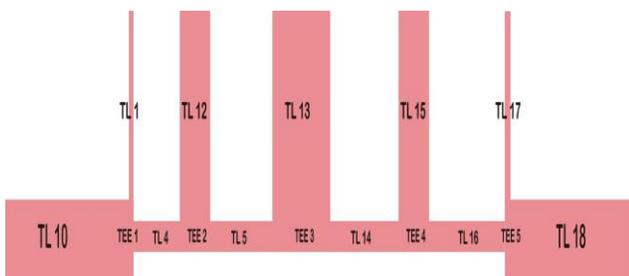


Fig. 18 Momentum generated layout of optimized circuit

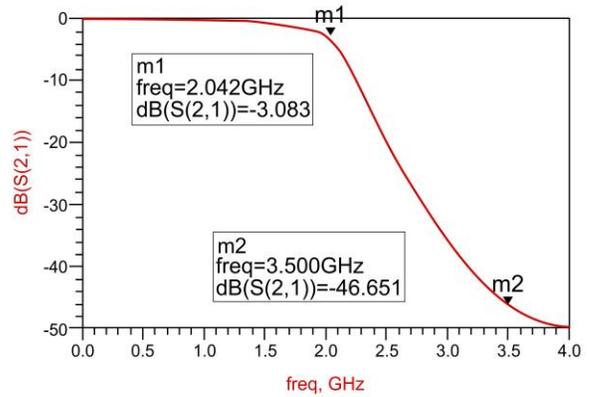


Fig. 19 Computer generated plot of low-pass filter

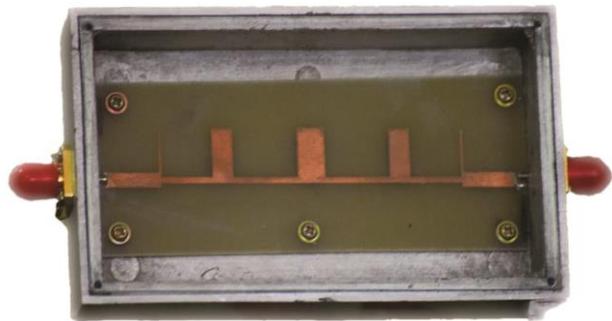


Fig. 20 Photograph of fabricated stub based low-pass filter



Fig. 21 Measured response using Network analyzer

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