Ultra-Compact LPF with Wide Stop-Band
Prashant Kumar Singh, Anjini Kumar Tiwary

Abstract – An ultra-compact, planar, wide stop-band and low cost low-pass filter (LPF) is proposed using microstrip stepped impedance hairpin resonator (SIHR). The wider stop band is achieved by loading the SIHR with radial stub within the SIHR area, which provides compactness. Further widening of stop-band is achieved by introducing quarter wavelength transmission stub at 50 Ω line, to produce transmission zero at higher frequency. The proposed LPF is designed for 3 dB cut-off frequency of 3 GHz having wide stop-band up to 12 GHz with three transmission zeroes in stop-band at 4.3 GHz, 7.5 GHz and 11 GHz. The microstrip circuit size is only 10 mm × 7.5 mm. The simulation result and measured result shows good agreement, which validates the proposed design.

Keywords – Low-pass filter (LPF), Stepped impedance hairpin resonator (SIHR), Radial stub, Microstrip filter.

I. INTRODUCTION

The recent trend of microwave and wireless system demands compact and high performance planar components. Microstrip low-pass filter (LPF) is one of the vital components in microwave and wireless system, which is used to suppress undesired harmonics. The conventional LPFs [1] suffer from gradual cut-off transition and narrow stop-band bandwidth. Various microstrip filter configurations [2-9] are developed to cope with these problems. The wider stop-band can be achieved by cascading multiple filter sections, which in turn increases the overall size of the filter. Compact structure and wider stop-band can also be achieved by using other methods like defected ground structure (DGS) [2-5] and electromagnetic band-gap (EBG) [6-7], while etched ground of DGS and periodic nature of EBG creates radiation problem. Several open circuited stubs are used to generate multiple transmission zeros in stop-band region to widen the stop-band [8], which cause the increased structural dimension. The compact LPFs are also designed using multiple Hilbert fractal lines [9] at the cost of poor stop-band response.

The radiation problem can be resolved by using planar structure. The planar stepped impedance hairpin resonator (SIHR) or planar radial stub attracted many researchers due to their compactness and easier fabrication. Conventional SIHRS have the limitation of narrow stop-band bandwidth. The wider stop-band bandwidth is achieved by cascading or modifying SIHRS [10-15]. Due to the advantage of wide stop-band and proper localization of zero-point impedance, radial stub is very good choice to extend the stop-band region [16]. The LPFs with wider stop-band is achieved by using radial stub [17-18].

In this paper, a new ultra-compact, planar, broad stop-band, low cost LPF is proposed. The ultra-compact LPF configuration with wide stop-band is achieved by inserting the radial stub within the area of SIHR, such that overall size of the filter remains same. Further extension of stop-band is achieved by inserting quarter wavelength resonator at 50 Ω line, such that overall size remains compact. The LPF is designed for 3 dB cut-off frequency of 3 GHz having wide stop-band from 3.6 GHz to 12 GHz with rejection level below 10 dB. The size of the filter is only 75 mm².

II. FILTER DESIGN

A. Elliptic Function LPF

The lumped element model of third order (n = 3) elliptic function low-pass filter (LPF) is shown in Fig. 1(a) and its microstrip stepped impedance hairpin resonator (SIHR) LPF configuration is shown in Fig. 1(b). For this the low-pass prototype values are selected as [1]:

\[ g_0 = g_4 = 1, \]
\[ g_{Cps} = g_1 = g_3 = 0.9471, \]
\[ g_{Ls} = g_2 = 1.0173, \]
\[ g_{Cg} = g_2' = 0.1205. \]

The L-C element values of this LPF, for 3 GHz cut-off frequency \( f_c \), can be calculated using the equations [1]:

\[ L_s = \frac{1}{2\pi f_c} Z_0 \cdot g_{Ls} \text{ in H}, \] (1)
\[ C_{ps} = \frac{1}{2\pi f_c Z_0} \cdot g_{Cps} \text{ in F}, \] (2)
\[ C_g = \frac{1}{2\pi f_c Z_0} \cdot g_{Cg} \text{ in F}. \] (3)

Here \( Z_0 = 50\Omega \) is input/output terminal impedance. The calculated values of inductance \( L_s \) and capacitances \( C_{ps} \) and \( C_g \) are given in Table 1. Advanced Design System (ADS2009) circuit simulator by Agilent Technologies is used for simulating lumped circuits. The simulated S-parameters response for the elliptic function LPF is shown in Fig. 2. The SIHR is composed of a transmission line having length \( l_s \) and coupled lines with length \( l_c \). All microstrip filter configurations are designed on the low cost FR-4 glass epoxy substrate with dielectric constant \( \varepsilon_r \) of 4.4, thickness \( h \) 1.56 mm and loss tangent (tan δ) 0.016. The microstrip
configurations are simulated using IE3D, full wave method of moments (MoM) based simulation software by Zeland. For microstrip SIHR realization, $Z_s$ (characteristic impedance of transmission line) is selected as $Z_s > \frac{(Z_{o-e}Z_{o-o})^{1/2}}{2}$. Here $Z_{o-e}$ and $Z_{o-o}$ are even and odd-mode impedances of parallel coupled lines. In SIHR configuration, $Z_s$ is the characteristic impedance of microstrip line having width $w_c$ and length $l_c$. The impedance of high and low impedance section are chosen as $Z_s = 111.5 \, \Omega$ and $Z_{c} = 41.5 \, \Omega$ correspond to their respective widths are $w_s = 0.5 \, \text{mm}$ and $w_c = 4 \, \text{mm}$, respectively. For the fixed value of $g = 0.5 \, \text{mm}$, even and odd-mode impedances can be calculated as $Z_{0-e} = 36.5 \, \Omega$ and $Z_{0-o} = 28.4 \, \Omega$. By using the calculated L-C values from Table 1, the dimensional parameters of SIHR can be calculated from the given equations [11]:

$$L_s = \frac{Z_s \cdot \sin(\beta_s l_s)}{2\pi f_c} \text{ in H,} \quad (4)$$

$$C_s = \frac{1 - \cos(\beta_s l_s)}{2\pi f_c Z_s \cdot \sin(\beta_s l_s)} \text{ in F,} \quad (5)$$

$$C_g = \frac{Z_{o-e} - Z_{o-o}}{4\pi f_c Z_{o-e}Z_{o-o} \cdot \cot(\beta_c l_c)} \text{ in F,} \quad (6)$$

$$C_p = \frac{1}{2\pi f_c Z_{o-e} \cdot \cot(\beta_c l_c)} \text{ in F,} \quad (7)$$

$$C_A = (0.012 + 0.0039 \cdot \epsilon_r) \cdot (w_c - w_s) \text{ in pF,} \quad (8)$$

$$C_{ps} = C_p + C_s + C_A,$$  \quad (9)

$$l_s = \frac{\sin^{-1}(2\pi f_c L_s / Z_s)}{\beta_s},$$  \quad (10)

$$l_c = \frac{\tan^{-1}[2\pi f_c Z_{o-o}(C_{ps} - C_s - C_A)]}{\beta_c}. \quad (11)$$

Here $\beta_s$ and $\beta_c$ are phase constants of single transmission line and coupled lines respectively, $L_s$ and $C_s$ are the equivalent inductance and capacitance of single transmission line, $C_g$ and $C_p$ are equivalent capacitances of parallel coupled lines, $C_A$ is the junction discontinuity between transmission line and coupled lines and $C_{ps}$ is the sum of capacitances of transmission line, coupled lines and junction discontinuity.

**TABLE 1**

<table>
<thead>
<tr>
<th></th>
<th>$L_s$</th>
<th>$C_{ps}$</th>
<th>$C_g$</th>
<th>$L_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated values</td>
<td>2.7 nH</td>
<td>1 pF</td>
<td>0.127 pF</td>
<td>-</td>
</tr>
<tr>
<td>Tuned values</td>
<td>4.4 nH</td>
<td>1 pF</td>
<td>0.127 pF</td>
<td>-</td>
</tr>
<tr>
<td>Modified values</td>
<td>3.8 nH</td>
<td>1 pF</td>
<td>0.075 pF</td>
<td>0.7 nH</td>
</tr>
</tbody>
</table>

**B. Modifications in L-C Values of LPF**

Since the simulated result in Fig. 2 shows slight variation in the desired cut-off frequency. To achieve the desired 3 GHz as 3 dB cut-off frequency, the lumped circuit is tuned using ADS2009. The tuned values of $L_s$, $C_{ps}$ and $C_g$ are given in Table 1 and respective S-parameters response is shown in Fig. 2. Further, the input and output port is tuned & some modifications are done to LPF lumped circuit as shown in Fig. 3(a) to achieve the good roll-off, accordingly microstrip configuration is modified as shown in Fig. 3(b). The modified values of all inductive and capacitive elements for this modified lumped circuit are given in Table 1. The respective S-parameters response is shown in Fig. 2. The dimensional parameters of the modified microstrip configuration can be calculated using Eqs. (4)-(11) by selecting the previous and tabular values $Z_s = 111.5 \, \Omega$, $Z_{o-e} = 36.5 \, \Omega$, $Z_{o-o} = 28.4 \, \Omega$. 
Zc = 41.5 Ω, ws = 0.5 mm, wc = 4 mm, g = 0.5 mm, 
Ls = 3.8 nH, Cps = 1 pF, Cg = 0.075 pF and La = 0.7 nH. The 
calculated dimensional parameters of this modified structure 
are given in Table 2 and respective S-parameter characteristic 
is shown in Fig. 4. Here, the 3 dB cut-off frequency is 
obtained as 3.7 GHz. So, further optimization is done using 
full wave electromagnetic simulator to get the 3 GHz cut-off 
frequency. The optimized dimensional parameters are also 
given in Table 2 and the respective S-parameter characteristic 
is shown in Fig. 4.

![Simulated S-parameter characteristics of microstrip LPF](image)

C. Stop-Band Extension

The stop-band of optimized microstrip LPF is only up to 
6.7 GHz. Further stop-band is extended by loading the SIHR 
with radial stub, such that overall size of microstrip 
configuration remains same, as shown in Fig. 5(a) by keeping 
all other parameters constant. Its lumped equivalent circuit is 
shown in Fig. 5(b). The radial stub section is introduced to 
create the transmission zero at 7.5 GHz to extend the stop-
bond region as has property of intrinsic wide stop-band 
characteristic and accurate localization of a zero-point impedance [16]. The radial stub with dimensional parameters 
outer radii (ro), inner radii (ri) and spanning angle (θ) can be 
analyzed as a series combination of inductance (Ls) and 
capacitance (Cs) [19-20]. The dimensional parameters of 
radial stub are obtained as ro = 4.2 mm, ri = 0.53 mm and 
θ = 40 degree. The S-parameter characteristic of this 
microstrip configuration is shown in Fig. 4. Further extension of stop-band is achieved by inserting transmission line 
(quarter wavelength resonator) at 50 Ω line to generate 
transmission zero at 11 GHz with total length 5.1 mm and 
width 0.3 mm as shown in Fig. 6, by keeping other 
dimensions constant. This is the proposed microstrip LPF 
configuration. The dimensions shown in Fig. 6 are as a = 2.1 
mm, b = 2.1 mm, c = 0.3 mm, s = 0.4 mm, w = 0.3 mm, x = 10 
mm, y = 7.5 mm. The simulated S-parameter characteristic 
of proposed LPF is depicted in Fig. 7. The simulation result 
shows the LPF with 3 dB cut-off frequency of 3 GHz having 
wide stop-band region with insertion loss (S21) below 10 dB 
up to 12 GHz.

![The proposed microstrip LPF](image)

### TABLE 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Calculated values</th>
<th>Optimized values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ws</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>wc</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>g</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>ls</td>
<td>6.4 mm</td>
<td>11 mm</td>
</tr>
<tr>
<td>la</td>
<td>1.1 mm</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>lc</td>
<td>4.15 mm</td>
<td>2.5 mm</td>
</tr>
</tbody>
</table>

III. EXPERIMENTAL RESULT

The proposed low cost, ultra-compact planar LPF with wide 
stop-band characteristic is designed by inserting radial stub 
and quarter wavelength resonator within the area of SIHR 
LPF structure. Further for validation, the proposed structure is 
fabricated using photolithographic method and tested using
Vector Network Analyzer (VNA). The fabricated microstrip LPF prototype is shown in Fig. 8. The comparative S-parameter characteristics of simulated and experimental microstrip LPF are shown in Fig. 9. The simulation and experimental results are in good agreement. Finally, the proposed LPF is compared with some other LPFs available in literature, which is given in Table 3.

![Fig. 8. Fabricated prototype of proposed microstrip LPF](image)

![Fig. 9. Comparative S-parameter characteristics of simulation and experiment](image)

**TABLE 3**

<table>
<thead>
<tr>
<th>Technique</th>
<th>3 dB cut-off freq. (GHz)</th>
<th>10 dB stop-band (GHz)</th>
<th>Size (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4] 2016</td>
<td>DGS</td>
<td>4</td>
<td>0.107 to 15</td>
</tr>
<tr>
<td>[13] 2009</td>
<td>SIHR</td>
<td>5.9</td>
<td>6.2 to 14</td>
</tr>
<tr>
<td>[14] 2011</td>
<td>SIHR</td>
<td>1.67</td>
<td>2 to 12</td>
</tr>
<tr>
<td>[15] 2015</td>
<td>SIHR</td>
<td>1.6</td>
<td>1.9 to 16</td>
</tr>
<tr>
<td>Proposed Work</td>
<td>SIHR + Radial</td>
<td>3</td>
<td>3.6 to 12</td>
</tr>
</tbody>
</table>

**IV. CONCLUSION**

A new type of ultra-compact LPF with wide stop-band using SIHR with radial stub is simulated, fabricated and tested. The size of the filter is only 75 mm². The simulation result and experimental result validate the proposed design. The 3 dB cut-off frequency of the proposed filter is 3 GHz having wide stop-band up to 12 GHz with insertion loss below 10 dB in stop-band region. The features of proposed LPF like ultra-compact structure, planar configuration and wide stop-band, make it suitable for modern wireless system.

**REFERENCES**


