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 mm^2.

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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]:

$$L_s = \frac{1}{2\pi f_c} \cdot Z_0 \cdot g_{Ls} \text{ in H,} \tag{1}$$

$$C_{ps} = \frac{1}{2\pi f_c Z_0} \cdot g_{Cps} \text{ in F ,} \tag{2}$$

$$C_g = \frac{1}{2\pi f_c Z_0} \cdot g_{Cg} \text{ in F.} \tag{3}$$

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 (ε_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 $Z_s > (Z_{0e} Z_{0o})^{1/2}$. Here Z_{0e} and Z_{0o} are even and odd-mode impedances of parallel coupled lines. In SIHR configuration, Z_c 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 Ω and Z_c = 41.5 Ω corresponds to their respective widths are w_s = 0.5 mm and w_c = 4 mm, respectively. For the fixed value of g = 0.5 mm, even and odd-mode impedances can be calculated as Z_{0e} = 36.5 Ω and Z_{0o} = 28.4 Ω. By using the calculated L-C values from Table 1, the dimensional parameters of SIHR can be calculated from the given equations [11]:

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

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

$$C_g = \frac{Z_{0e} - Z_{0o}}{4\pi f_c Z_{0e} Z_{0o} \cdot \cot(\beta_c l_c)} \text{ in F,} \tag{6}$$

$$C_p = \frac{1}{2\pi f_c Z_{0e} \cdot \cot(\beta_c l_c)} \text{ in F,} \tag{7}$$

$$C_\Delta \cong (0.012 + 0.0039 \cdot \varepsilon_r) \cdot (w_c - w_s) \text{ in pF,} \tag{8}$$

$$C_{ps} = C_p + C_s + C_\Delta , \tag{9}$$

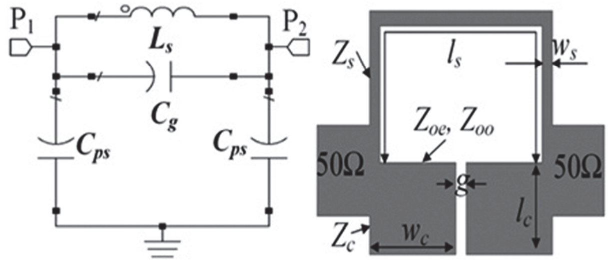
$$l_s = \frac{\sin^{-1}(2\pi f_c L_s / Z_s)}{\beta_s} , \tag{10}$$

$$l_c = \frac{\tan^{-1}[2\pi f_c Z_{0e}(C_{ps} - C_s - C_\Delta)]}{\beta_c} . \tag{11}$$

Here β_s and β_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_Δ 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
L-C VALUES TABLE FOR LUMPED LPF

	L_s	C_{ps}	C_g	L_a
Calculated values	2.7 nH	1 pF	0.127 pF	-
Tuned values	4.4 nH	1 pF	0.127 pF	-
Modified values	3.8 nH	1 pF	0.075 pF	0.7 nH



(a) (b)

Fig. 1. (a) Lumped element model of third order elliptic function LPF (b) Conventional microstrip SIHR LPF

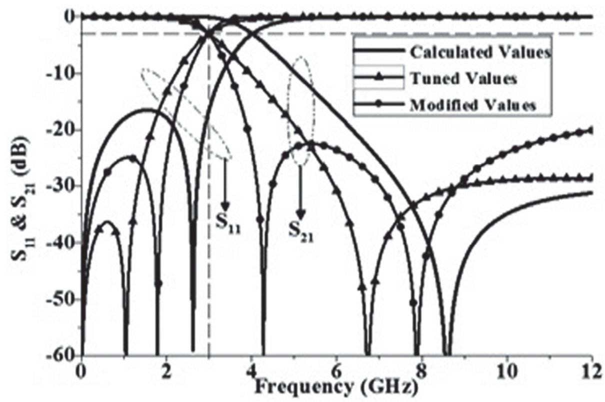
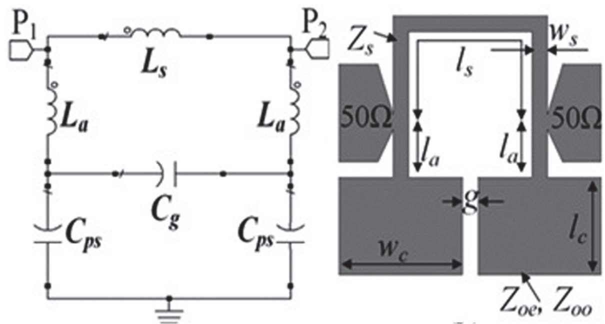


Fig. 2. Simulated S-parameters responses of lumped LPF



(a) (b)

Fig. 3. (a) Lumped element elliptic function LPF with some modification; (b) its microstrip SIHR realization

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 Ω, Z_{0e} = 36.5 Ω, Z_{0o} = 28.4 Ω,

$Z_c = 41.5\ \Omega$, w_s = 0.5 mm, w_c = 4 mm, g = 0.5 mm, L_s = 3.8 nH, C_{ps} = 1 pF, C_g = 0.075 pF and L_a = 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.

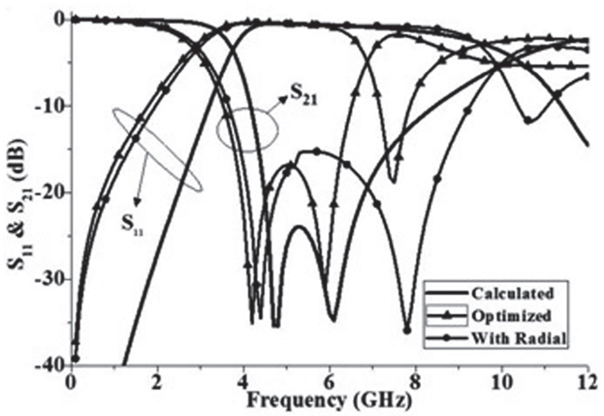
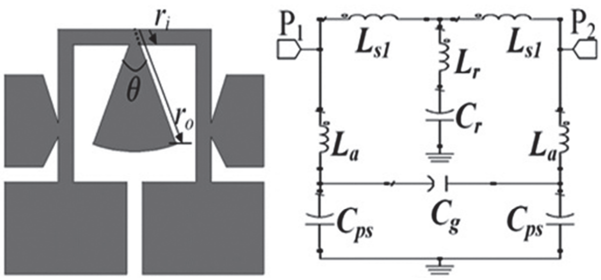


Fig. 4. Simulated S-parameter characteristics of microstrip LPF



(a) (b)

Fig. 5. (a) Microstrip SIHR loaded with radial stub, (b) its lumped equivalent model

TABLE 2
DIMENSIONAL PARAMETERS OF MODIFIED MICROSTRIP CONFIGURATION

Parameters	Calculated values	Optimized values
w_s	0.5 mm	0.5 mm
w_c	4 mm	4 mm
G	0.5 mm	0.5 mm
l_s	6.4 mm	11 mm
l_a	1.1 mm	1.5 mm
l_c	4.15 mm	2.5 mm

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-band 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 (r_o), inner radii (r_i) and spanning angle (θ) can be analyzed as a series combination of inductance (L_r) and capacitance (C_r) [19-20]. The dimensional parameters of radial stub are obtained as r_o = 4.2 mm, r_i = 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_t = 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 (S_{21}) below 10 dB up to 12 GHz.

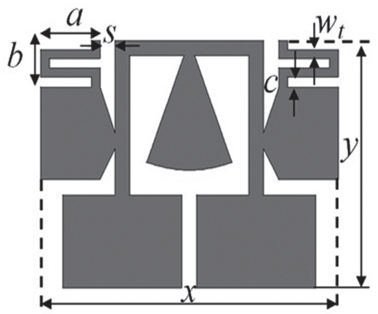


Fig. 6. The proposed microstrip LPF

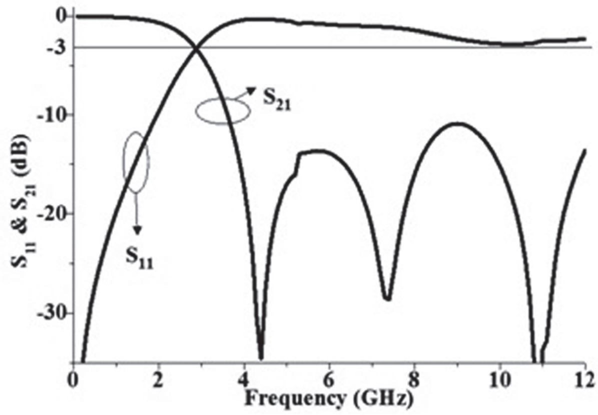


Fig. 7. The simulated S-parameter characteristic of proposed microstrip LPF

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

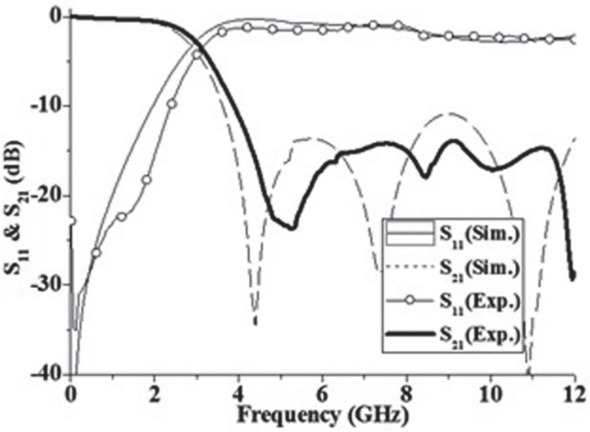


Fig. 9. Comparative S-parameter characteristics of simulation and experiment

TABLE 3
COMPARISON OF PROPOSED LPF WITH OTHER LPFS

	Technique	3 dB cut-off freq. (GHz)	10 dB stop-band (GHz)	Size (mm^2)
[4] 2016	DGS	4	4.07 to 15	569.28
[13] 2009	SIHR	5.9	6.2 to 14	85.91
[14] 2011	SIHR	1.67	2 to 12	100
[15] 2015	SIHR	1.6	1.9 to 16	173
Proposed Work	**SIHR + Radial**	**3**	**3.6 to 12**	**75**

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 mm^2. 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.

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