Method to Improve the Roll-Off and Stopband Response in Low Pass Filter Using Patch Resonators for Modern Wireless Communication

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Abstract. In this paper, several types of patch resonators design procedure are proposed and analysed to improve the roll-off and stopband response in low pass filter. The proposed patch resonators consist of T-shaped patch resonator (TS-PR) that provides instant sharp roll-off and also dual folded T-shaped resonator (DFTS-PR) that improves the roll-off of the previous TS-PR. The transmission zeros of the resonators can be adjusted by varying length and width of high and low impedance microstrip lines. It has been shown that the final design of the patch resonators provides sharp roll-off and acceptable stopband bandwidth by adopting both TS-PR and DFTS-PR. The proposed low pass filter with 3-dB cut-off frequency ($f_c$) of 5.26 GHz exhibits excellent roll-off rate of 82.2 dB/GHz from 5.5 GHz to 11.7 GHz. Moreover, the transition of the proposed filter is 0.45 GHz which contributes to a sharper transition band from passband to stopband.

1. Introduction
Low pass filter is one of the indispensable blocks in wireless communication system especially at the receiver and transmitter circuits. The approach of the conventional model is based on cascading high- and low-impedance transmission line segments. Such filters are usually called as stepped-impedance low pass filter (SILPF) or hi-Z and lo-Z low pass filter and suffer from narrow stopband and poor cut-off frequency response [1][2]. Although the limitation can be improved by increasing the number of filters elements, still other drawback will create in terms of larger physical size and degradation of pass band.

With the rapid development of wideband wireless communication, the need of the microstrip low pass filter that has high selectivity and ultra-wide with deep rejection level of stopband is in highly demand especially in radar and RFID. Recently, several techniques have been proposed by the researchers to improve the low pass frequency response characteristics. According to [3] a 3rd order low pass filter utilizing radial stubs is presented, which provided ultra-wide rejection and compact size. However, the transition band is gradual. In [4] a symmetrically triangular and polygonal patch resonators are loaded to the transmission line and provide wide stopband, but these types of filter suffered from low selectivity. An elliptic low pass filter with slit-loaded tapered microstrip resonator cell is adopted in [5] and resulted a sharp cut-off frequency, but the filter requires large area, and the
stopband rejection level is only 10dB. Coupled line-hairpin unit is utilized in [6][7] which exhibit wide rejection bandwidth, but high return loss in the passband.

Another technique to design low pass filter is proposed by employing various forms of defective ground structures (DGS). Low pass filters that embedded DGS in their structure usually achieved wide stopband and high suppression level. Nevertheless, the drawback is concerning energy leakage through the ground plane and considering enclosure or Electromagnetic Compatibility (EMC) box to prevent the leakage. The study in [8] proposed a low pass filter using open complimentary split ring resonator and dumbbell shape DGS. Furthermore, according to [9] by implementing a horn-shaped slot and arc-head slots as DGS inside the resonator cells, sharp cut-off and wide rejection is achieved. A high performance low pass filter is presented in [10] using coupled C-shaped DGS and radial stub resonators for microwave mixer applications. The proposed filter achieved low insertion loss and sharp transition band.

Meta-material is the technique that could overcome filter physical size problem. A complimentary hex-omega structure is loading to the ground plane and the roll-off performance of the filter is improved with significantly reduce the size of the filter about 36.2% [11]. In addition, split ring resonators (SRRs) and complimentary split ring resonator are exploited to obtain low pass filter metamaterial type. As reported in [12] higher selectivity and better group delay in the passband is presented.

In this work, a compact low pass filter adopting TS-PR and DFTS-PR is proposed and analyzed. The proposed structure is designed and analyzed in three (3) sections. In the first and second sections, a TS-PR and a single folded TS-PR with both lumped equivalent circuits are investigated. Next section is the cascaded structure between TS-PR and DFTS-PR to improve the roll-off and the stopband bandwidth.

2. T-shaped patch resonator (TS-PR) design and analysis
The main advantage of the TS-PR is it can create instantaneous attenuation at the resonance frequency; therefore this feature can boost up the function of the low pass filter to obtain wider stopband [13]. Figure 1 shows the physical layout of the microstrip structure for TS-PR. The proposed resonator composed of a straight stub that act as inductive straight stub of impedance $Z_{La}$ and loaded by a low impedance capacitive rectangular patch of impedance $Z_{Ca}$. The value for both $Z_{La}$ and $Z_{Ca}$ are 109.4Ω and 24.24Ω which fulfill the design criteria as $Z_{Ca} < Z_o < Z_{La}$, where $Z_o$ is the characteristics impedance of 50Ω feed line [14][15]. Both are symmetrically loaded on a high impedance transmission line.

The combination between the straight stub and rectangular patch forms a series of L-C resonator namely as TS-PR without considering the fringe and parasitic capacitance. The physical dimension of the layout in figure 1 are $l_{a1} = l_{a2} = 4.79$mm, $l_1 = 3.2$mm, $l_2 = 0.8$mm, $w_1 = 0.2$mm and $w_2 = 2.0$mm. The lumped equivalent circuit of TS-PR is presented in figure 2. In this model, $L_{a1}$ and $L_{a2}$ are the equivalent inductance of the transmission line of lengths $l_{a1}$ and $l_{a2}$ with width of $w_1$, respectively; $C_{l1}$ denotes the inductance of the straight stub with length of $l_2$ whereas $C_{l1}$ is the capacitance of the rectangular patch with length of $l_1$ and width of $w_2$. 
The value of inductance, \( L \) in unit henry (H) can be calculated using Equation (1) and the value of capacitance, \( C \) in unit farad (F) can be determined by using Equation (2). The value of the lumped elements for TS-PR are \( L_{a1} = L_{a2} = 2.45 \text{nH}, L_{d1} = 0.48 \text{nH} \) and \( C_{l1} = 0.46 \text{pF} \). The simulated result of physical layout in Figure 3 is depicted in Figure 5 and is accomplished using EM simulator.

\[
L = \frac{1}{\omega} x Z_{H} x \sin \left( \frac{2\pi l_{x}}{\lambda_{g}} \right)
\]  
(1)

\[
C = \frac{1}{\omega} x \frac{1}{Z_{L}} x \tan \left( \frac{\pi l_{x}}{\lambda_{g}} \right)
\]  
(2)

3. Single folded TS-PR design and analysis

Single folded TS-PR consists of a high impedance straight stub that has been folded and connected in series with a low impedance rectangular patch. The previous TS-PR is modified by folding the single straight stub to decrease the overall area of the T-shaped patch resonator. Figure 4 illustrates the physical layout of a single folded TS-PR. The dimensions of the physical layout are \( l_{a1} = l_{a2} = 4.79 \text{mm}, d_{1} = 1.8 \text{mm}, d_{2} = 0.5 \text{mm}, d_{3} = 1.1 \text{mm}, w_{1} = 3.2 \text{ mm}, w_{2} = 2.0 \text{mm} \) and \( \text{T-T}' = 0.2 \times 0.2 \text{ mm}^2 \). The single folded TS-PR with shunt capacitors and series inductor is modelled in figure 5.
Figure 4. Physical layout of a single folded TS-PR

Figure 5. Lumped equivalent model of a single folded TS-PR

In this equivalent circuit, $L_{a1}$ and $L_{a2}$ represent the equivalent inductance of length $l_{a1}$ and $l_{a2}$ with width $w_1$ respectively. $L_{m1}$ and $L_{m2}$ represent the equivalent inductance of straight stub of length $d_1$ and $d_2$. The bended T-T’ of single straight stub is modelled as equivalent T-network. $C_{m1}$ represents the capacitance of rectangular patch with length $d_3$ and width $w_2$. The value of L and C of T-network can be obtained from Equation (3) and (4) (Pozar, 2005). The value of the lumped elements for a single folded T-shaped resonator are $L_{a1} = L_{a2} = 2.45\text{nH}$, $L_{m1} = 1.07\text{nH}$, $L = 0.087\text{nH}$, $C = 0.77\ \text{pF}$, $L_{m2} = 3.03\text{nH}$ and $C_{m1} = 0.46\text{pF}$. The simulated result of single folded TS-PR is depicted in figure 5. The proposed structure of a single folded TS-PR produces a transmission zero ($TZ_2$) at 7.7GHz with -44.70dB attenuation level.

$$C\left(\frac{pF}{m}\right) = \begin{cases} \frac{(14\varepsilon_r + 12.5)W}{h} - \left(1.83\varepsilon_r - 2.25\right) + \frac{0.02\varepsilon_r}{W}\frac{W}{h} & \text{for } \frac{W}{h} < 1 \\ \frac{(9.5\varepsilon_r + 1.25)W}{h} + 5.2\varepsilon_r + 7.0 & \text{for } \frac{W}{h} \geq 1 \end{cases}$$

(3)

$$\frac{L}{h}(nH/m) = 100\left\{4\sqrt{\frac{w}{h}} - 4.21\right\}$$

(4)

where $w$ is the width and $h$ are the thickness of the microstrip line in mm.
By connecting one more unit of folded TS-PR resonator at the opposite side, the selectivity as well as the stopband bandwidth is improved. The new structure is called as DFTS-PR. Figure 7 and figure 8 present the physical layout and comparison of simulated $S_{21}$ characteristics between a single folded TS-PR and DFTS-PR.

As seen in figure 8, for a single folded TS-PR, one transmission zero, $T_{Z1}$ is obtained at 6.6 GHz with attenuation level -42.43 dB. By applying DFTS-PR, a new transmission zero, $T_{Z2}$ is found at the same frequency, 6.6 GHz with high attenuation level -74.36 dB. DFTS-PR improves the stopband bandwidth and provide better roll-off rate of 26.4 dB/GHz from -3dB to -40 dB compare to a single folded TS-PR which is only 17.1 dB/GHz.

4. Cascaded structure of TS-PR and DFTS-PR
In order to have wider stopband bandwidth and achieve better roll-off rate, TS-PR is combined with DFTS-PR. By cascading structure of TS-PR at upper part of main high impedance transmission line and DFTS-PR at lower part of main high impedance transmission line, the roll-off and stopband bandwidth are greatly improved. Figure 9 shows the physical layout of combined structure of TS-PR and DFTS-PR. Figure 10 illustrates the comparison of simulated $S_{21}$ between TS-PR, DFTS-PR and combination of TS-PR and DFTS-PR.
Figure 9. Physical layout of a single folded TS-PR

Figure 10. Comparison of simulated $S_{21}$ between single folded TS-PR, DFTS-PR and combination of TS-PR and DFTS-PR.

As observed from Error! Reference source not found., the roll-off rate, $\zeta$ for TS-PR is 19.1 dB/GHz at 40 dB attenuation level whereas by cascade between TS-PR and DFTS-PR, three new transmission zeros which is $T_{Z3}$, $T_{Z4}$ and $T_{Z5}$ are obtained at 5.8 GHz, 6.5 GHz and 7 GHz. The condition of adding more transmission zeros lead to the wider stopband bandwidth. The attenuation level of the three transmission zeros are -52.99 dB, 70.32 dB and -73.41 dB. The roll-off rate, $\zeta$ is increased up to 82.22 dB/GHz which contributes to a sharper transition band from passband to stopband, results a better roll-off rate. Error! Reference source not found. shows the comparison of transition and roll-off rate between single folded TS-PR, DFTS-PR and combination of TS-PR and DFTS-PR.

Table 1. Comparison of transition and roll-off rate between single folded TS-PR, DFTS-PR and combination of TS-PR and DFTS-PR.

| Resonator                  | Transition (GHz) | Roll-off rate (dB/GHz) |
|----------------------------|------------------|------------------------|
| TS-PR                      | 1.94             | 19.1                   |
| DFTS-PR                    | 1.40             | 26.4                   |
| Cascaded structure of TS-PR and DFTS-PR | 0.45             | 82.2                   |

5. Conclusion
In this paper, the design of several patch resonators include TS-PR and DFTS-PR have been presented to improve the roll-off rate and stopband bandwidth in low pass filter. An excellent roll-off rate up to 82.2 dB/GHz can be realised through the combination of TS-PR and DFTS-PR. From the simulation results, the low pass filter based on the proposed patch resonators method offers either improvement of the roll-off and the stopband bandwidth. The introduced low pass filter using patch resonators are design to meet the requirement of modern wireless communication systems.
6. References

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