Very Compact Reconfigurable Planar Filter With Wide-stopband Performance for Sub-6 GHz 5G Systems

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Abstract—This manuscript introduces a new and very compact planar reconfigurable bandpass to band-pass/low-pass filter covering the 0 to 1 GHz and 3.4 to 3.8 GHz bandwidth for the fifth-generation (5G) systems. The patch filter uses three trisection resonators with 50 Ω transmission lines for input and output feedings. To realize high selectivity, finite transmission zeros have been successfully realized on the upper and lower sides of the in-band transmission. By employing another resonator between the input and output transmission line feedings, lowpass performance and reconfigurability characteristics are obtained. The cross-coupling factors between the adjacent and non-adjacent resonator lines are optimized to achieve the required performance. The presented filter is analyzed and optimized with the aid of the computer simulation technology (CST) simulator, and is implemented and printed on a Rogers RO3010 dielectric material with a relative permittivity of 10.2 and loss tangent of 0.002. Also, the filter has a very compact size of 10×8×1.27 mm³. Good agreement is obtained between the simulation and measurement characteristics.

Keywords—band-pass, low-pass, compact, reconfigurable, planar filter, 5G.

I. INTRODUCTION

Generally, radiofrequency (RF) interference and harmonic signals are causing big issues for current and future wireless applications and therefore extensive researches have been carried out on RF filters in the last few years [1-10]. Microstrip band-pass filters (BPFs) are commonly used to filtering out, attenuate as well as suppress the harmonic frequencies and the unwanted noise signals in different applications, mainly in RF and microwave (MW) [11-17]. Recently, the 5G spectrum has been suggested by Ofcom for use in sub-6 GHz (700 MHz and 3.6 GHz) and millimeter wave (26 GHz) [18].

Therefore, many planar band-pass filters are used to suppress the noise signals in several 5G systems [19-27]. For any planar band-pass filter, the number of poles and zeros, input/output external quality factors, coupling coefficients and the geometry of the filter are important factors that affect the filter’s function [28]. Most microstrip filter miniaturization approaches are aiming to determine and adjust these parameters [29-32]. Also, many design approaches have been proposed by some researchers like stepped-impedance resonators (SIR) structures, combline filters, open-ring resonators, coupled-line resonators, and differential-fed filters [33-37].

Recently, reconfigurable/tunable RF and MW elements are considered as interesting subjects for many researchers engineers to achieve compact systems and miniaturized RF front-end with promised functions [38-49]. A varactor-tuned planar reconfigurable band-pass filter was studied and presented to obtain a constant bandwidth in [42]. The resonance frequencies for both the odd- and even- modes are adjusted to control the bandwidth since there is no coupling between these two modes. The filter achieved a good selectivity with an insertion loss of around 3 dB and a return loss of about 12 dB at the center frequency. By applying 2.2-22 v reverse biasing voltage across the diode, the center frequency is tuned from 0.61 to 1.1 GHz with a constant impedance bandwidth of 90 MHz was observed over this range.

In [43], a planar reconfigurable band-pass filter is introduced by tuning two finite transmission zeros (TZs) using two diodes. A 0.21-30.02 v reverse biasing voltage is applied across the varactor to tune the center frequency from 1.3 GHz to 1.9 GHz. The filter presents an insertion loss of better than 4 dB, a return loss of more than 18 dB, and impedance bandwidth of about 580 MHz (fractional bandwidth of about 10%). A stopband attenuation of better than 24 dB is also observed by utilizing two transmission zeros.

A notch dual-mode reconfigurable band-stop microstrip filter based on two varactor switches is presented in [45]. The filter is designed based on controlling the inductive and capacitive coupling of the input and output feeding lines. The proposed filter requires a small area of 0.14×0.18 and provides a continuous tuning range for the center frequency from 0.8 GHz to 1.1 GHz. The filter has a stopband fractional bandwidth of about 17% and presents a return loss of more than 6 dB and an insertion loss of less than 15 dB at the operation frequency. Unlike other proposed designs, the inductive coupling is realized by designing the inductor on the ground plane. As a result, this design does not require a more complicated structure and so providing a high degree of freedom to control the characteristics of the proposed planar filter.

This manuscript proposes a very compact three poles reconfigurable planar filter with low-pass and band-pass characteristics. The filter is designed and simulated using the CST simulator. Two configurations with two operational
bandwidths from 0 to 1 GHz and 3.4 to 3.8 GHz, suitable for sub-6 GHz 5G systems, were observed. The presented filter is also printed on a Rogers RO3010 substrate with a relative permittivity of 10.2 and a loss tangent of 0.002. The filter has a very compact size of $10 \times 8 \times 1.27 \text{ mm}^3$. Besides, the proposed filter configuration can be easily modified and integrated with the microstrip antennas to implement the so-called filtering antenna design [49-54]. The proposed microstrip filter, with the designing procedures, and the simulation and measurement results are explained and presented in the next sections.

II. 3-POLE LUMPED-ELEMENT BAND-PASS FILTER DESIGN

A three-pole lumped-element low-pass filter prototype is firstly designed using the design equation and parameters detailed in [11] with Butterworth characteristics. The designed resonating circuit is working on 3.6 GHz frequency and has a fractional bandwidth of 12% and a low ripple factor of 0.002. The design parameters for the lumped-element low-pass filter are indicated by $(g_i)$ for $i=0$ to $n+1$ and, at the cut-off frequency $(\Omega_c)$ of 1 rad/s, they are obtained as follow:

$g_0 = g_4 = 1 /g_1884, \quad g_1 = g_3 = 1 \text{ H} \quad \text{and} \quad g_2 = 3 \text{ F}.$

After achieving these parameters and at the normalized characteristic impedance $g_0 = 1$ and cut-off frequency 1.0 rad/s, frequency and element transformations are conducted to achieve the lumped-element circuits of the proposed band-pass filter. The angular frequency transformation affects only the reactive parameters and does not affect the resistive parameters. The impedance transformation factor $Z_0 = 50$ and the angular operating frequency $\omega$ and, respectively, to realize the best matching at the desired frequency. It is also found that $L_1 = L_2 = L_3 = 159 \text{ nH}$, $C_1 = C_3 = 12.16 \text{ pF}$ and $C_2 = 0.12 \text{ pF}$. Consequently, and in line with the steps shown above, the lumped-element equivalent circuit of the introduced band-pass filter can be designed as illustrated in Fig. 1. The return/insertion losses, group delay, and phase of $S_{21}$ for the proposed lumped-element band-pass filter are presented in Fig. 2.

![Fig. 1. Lumped-elements of the filter.](image)

Also, the input and output external quality factors can be calculated as follows:

$$Q_i = Q_o = \frac{g_0 g_1}{\text{FBW}} = \frac{g_2 g_3}{\text{FBW}}$$

(1)

Where FBW represents the fractional bandwidth of the proposed filter, which is selected to be 12% for this design. While the input and output coupling coefficients can be determined by:

$$M_{12} = \frac{\text{FBW}}{\sqrt{g_1 g_2}}$$

(2)

III. DESIGN AND ANALYSIS OF 3-POLE RING RESONATOR PLANAR BAND-PASS FILTER

As shown in [11], Richards’ formulas are utilized to transform the proposed lumped-element band-pass filter into the planar microstrip line model using an open-loop ring resonator technique. As shown, the basic configuration of the introduced patch filter is depicted in Fig. 3, where three-ring resonators, namely $R_1$, $R_2$ and $R_3$, are used and excited by two input and output transmission line ports (port 1 and port 2, respectively) each with 50 $\text{O}$ impedance and therefore providing a compact size structure without requiring the vias. The structure has a Rogers RO3010 substrate with $h = 1.27 \text{ mm}$, a dielectric constant of 10.1 and loss tangent ($\tan \delta$) of 0.0018. The design parameters are chosen to work on the operation frequency of 3.6 GHz for sub-6 GHz 5G wireless communications. By using the CST software, the designed microstrip trisection filter can also be implemented by the simple equivalent circuit model as illustrated in Fig. 4.

![Fig. 2. Lumped-element filter performance.](image)

![Fig. 3. The configuration of the basic filter design.](image)

![Fig. 4. Equivalent circuit of the designed patch filter.](image)
Similar to what is shown in the analysis of the lumped element filter design, the external quality factors for the input and output ports of the designed trisection band-pass filter can be denoted by $Q_i$ and $Q_o$, respectively. Also, $M_{12}$ and $M_{23}$ represent the coupling coefficient factors between the resonators $R_1$ and $R_3$, while the cross-coupling coefficient between the resonators $R_1$ and $R_3$ is denoted by $M_{13}$. As long as the designed filter is symmetric structure, the input and output external quality factors and coupling coefficients will also be identical and will be calculated from one terminal. Fig. 5 illustrates the configuration and performance used to determine the external quality factor.

Then, equation (3) has been applied to plot the external quality factors corresponding to the feeding point distance indicated by $S_1$ or $S_2$.

$$Q_e = f_0 / \Delta f_{3dB}$$  

Fig. 5. Filter analysis to find $Q_e$: (a) Loaded configuration, (b) return loss performance, and (c) $Q_e$.

Additionally, the coupling coefficient analysis for the adjacent resonators $R_1$ and $R_3$ is determined and analyzed as shown in Fig. 6. Equation (4) has been applied to determine and plot the coupling coefficient factor by changing the gap between the resonators ($w_1$).

$$M_{13} = \frac{(f_2^2-f_1^2)}{(f_2^2+f_1^2)}$$  

Fig. 6. Filter analysis to find $M_{13}$: (a) Design used, (b) Return loss performance, and (c) $M_{13}$.

Similarly, the coupling coefficient analysis for the non-adjacent resonators $R_1$ and $R_2$ is determined and analyzed as shown in Fig. 7. Equation (5) has been applied to determine and plot the coupling coefficient factor by changing the gap between the resonators ($w_2$).

$$M_{42} = M_{23} = \frac{(f_2^2-f_1^2)}{(f_2^2+f_1^2)}$$  

Fig. 7. Filter analysis to find $M_{12}$: (a) Design used, (b) Return loss performance, and (c) $M_{12}$.

According to the above analysis, the proposed trisection filter can be designed as illustrated in Fig. 8. All the dimensions are also optimized using the CST simulator and illustrated in Table 1. Fig. 9 shows the simulated $s$-parameters of the designed 3-pole microstrip filter. The simulated $s$-parameter shows that the presented design has an insertion loss of less than 1 dB and a return loss of more than 25 dB at the resonance frequency.
IV. RECONFIGURABLE FILTER DESIGN AND PERFORMANCE

To achieve the lowpass characteristics and the reconfigurability property, the parasitic transmission line is loaded to the designed 3-pole band-pass filter. The length of the resonator is selected to be \( \lambda_{g0}/2 \approx 20 \text{ mm} \) and 0.35 mm width, where \( \lambda_{g0} \) is representing the guided wavelength at the center frequency. Fig. 10 illustrates the geometry of the proposed reconfigurable microstrip filter. It should be noted that the size of the design is very compact even with the merit of reconfigurability. Fig. 11 illustrates the simulated and measured results of the proposed reconfigurable filter for both on- and off-configuration in addition to photographs of the fabricated filter.
gab (without shorting metal). The simulation results illustrate that the proposed BPF has an insertion loss of less than 1 dB at the resonant frequency 3.5 GHz, with a return loss of more than 20 dB. Fig. 11(b) shows the s-parameter results of the return loss and the insertion loss of the introduced dual-band filter in the on-state configuration for tackling the lowpass and bandpass filter characteristics. Here, the on-state diode is simply represented by a shorting metal. At the resonant frequency 700 MHz, the simulation results of the first passband show that the proposed filter has an insertion loss of 0.07 dB with return loss better than 19 dB for the low-pass filter configuration. On the other hand, at the resonant frequency 3.5 GHz, the performance of the second passband shows that the introduced structure offers an insertion loss of 0.5 dB with a return loss of more than 30 dB for the bandpass filter configuration. Furthermore, and roll-off skirt rejection, some of the finite transmission zeros have been successfully generated in the upper/lower edges of the passband as shown in Fig. 11. The presented reconfigurable band-pass filter has many advantages, and these include a very small size and simple configuration, (2) wide-stopband and good selectivity, and (3) very low measured losses and good return performance.

V. CONCLUSION

A new and very compact reconfigurable microstrip band-pass and lowpass filter is presented in this paper to covering 0 to 1 GHz and 3.4 to 3.8 GHz spectrum for sub-6 GHz 5G wireless applications. To achieve the low-pass characteristics and reconfigurability properties, another transmission line is utilized between the input and output ports for the same 3-pole structure. Finite transmission zeroes are successfully realized on the upper and lower edges of the passbands to increase the selectivity of the proposed reconfigurable filter. Good agreement is observed between the simulation and measurement results.

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