COMPACT TUNABLE MICROSTRIP FILTER WITH WIDE-STOPBAND RESTRICTION AND WIDE TUNING RANGE FOR 4G AND 5G APPLICATIONS

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Abstract

This paper presents a compact planar tunable filter covering the 2.5 to 3.8 GHz spectrum for 4G and 5G wireless communications using a new hybrid technique. The microstrip filter uses five coupled line resonators with $\lambda/4$ open-circuited stubs. The coupling between the resonators is adjusted to tune the centre frequency with Butterworth characteristics. The proposed bandpass filter (BPF) is designed on a Rogers RO3010 substrate with a relative dielectric constant of 10.2 and a compact size of $13 \times 8 \times 0.81$ mm³. The coupling coefficients between the adjacent resonators, external quality factors, varactor diodes and biasing circuit are designed to resonate the tunable filter at 3.5 GHz. The bandwidth is adjustable between 90 and 110 MHz with return losses between 15 to 25 dB and insertion loss around 0.8 dB. Computer simulation technology (CST) software is used to simulate and optimize the designed tunable filter, with hybrid co-simulation between CST MWS and CST DS is used to implement the structure, taking into account the SPICE model for the varactor diodes and the effect of the biasing circuit.

1 Introduction

Radio frequency noise is a serious issue in recent applications of wireless channels such as in green communications and wideband radar systems [1-4]. Planar bandpass BPFs are generally used to suppress unwanted noise signals in many wireless systems [5], mainly in radio frequency (RF) and microwave (MW) communications because of their active role to reject the spurious frequencies. Currently, next-generation technologies are being suggested for use in low-band (700 MHz), mid-band (3.6 GHz) and millimetre wave band (26 GHz) [6]. BPF is used in different 5G applications for rejecting noise frequencies [7,8]. A BPF consists of a number of poles, and the designs of the resonators and the number of elements define the filter properties. Most planar filter miniaturization techniques try to minimize and optimize these parameters [9-16]. Many approaches and structures have been presented such as Stepped-impedance resonators (SIR), combline, ring resonators, parallel-coupled lines, and stub impedance resonators [17-23].

A planar microwave tunable bandpass filter using a varactor diode is investigated for controlling a constant bandwidth in [17]. Tuning is achieved by controlling the resonant frequencies for both the odd and even modes as there is no coupling between these modes. In [18], a planar tunable filter uses two varactor diodes to adjust two transmission zeros (TZs). The resonant frequency and the bandwidth are adjusted with a wide tuning range of about 590 MHz (1.5 to 2.1 GHz)

by controlling the DC biasing voltage across to the varactor diodes. In [19], a compact reconfigurable microstrip filter with constant characteristic is presented. By controlling the DC biasing voltage of one varactor diode, the filter is reconfigurable from 3.4 to 3.8 GHz with a 10% fractional bandwidth.

Recently, many designs of reconfigurable microstrip filters have been proposed and investigated. Chen et al. [21] described a second-order filter with compact size and constant bandwidth. Two varactor diodes tune the resonant frequency between the higher and lower modes of operation with a range of 1.2 to 1.9 GHz and constant bandwidth of 39 MHz. Its properties of small size ($0.06 \lambda_g \times 0.27 \lambda_g$), continuous reconfigurability, simple design, and wide-ranging frequency make the filter suitable for current wireless communications. Ebrahimi et al. [22] propose a notch tunable band-stop filter by using two varactor diodes. The second-order filter illustrates a continuous tuning range of the resonant frequency of 0.7 to 1 GHz with a compact structure of size $0.15 \lambda_g \times 0.17 \lambda_g$. Unlike the previous structures, the inductive coupling is obtained using an inductor in the ground layer of the microstrip.

This article presents a compact fifth-order microstrip open-ended resonator filter, to cover the frequency band of 2.5 to 3.8 GHz for 4G and sub-6 GHz 5G applications. It is simulated using a hybrid co-simulation between CST MWS and CST DS tool. The filter is designed on a Rogers RO3010 substrate with a relative dielectric constant of 10.2 and a

compact size of $13 \times 8 \times 0.81 \text{ mm}^3$. Controlling the DC biasing voltage across two varactor diodes gives a wide tuning range of about 2.5 to 3.8 GHz, with 90-110 MHz operational bandwidth. Significantly, this filter can be easily developed and integrated with antenna structures [24], to produce the so-called “filtenna” [25]. The proposed tunable BPF, with the design procedure and the achieved performance, is presented in the following sections.

2. Design of Three-pole Coupled-Line Resonator Filter

The geometry of the proposed planar bandpass filter is shown in Fig. 1. The filter consists of three-pole coupled line resonators and is fed by two ports of 50Ω input impedance. The resonators are open-circuited at one end and short-circuited through vias at the other end with a $\lambda/4$ physical length. The filter has a transmission line feed and uses a Rogers RO3010 substrate, with $h = 0.81 \text{ mm}$, $\epsilon_r = 10.2$ and loss tangent = 0.0022. The resonant frequency of 3.8 GHz is chosen as suitable for 5G applications. The configuration of the 3-pole bandpass filter is shown in Fig. 1. The length of the resonators (R_1 and R_3) with 12 mm width and for the resonator R_2 is 7.7 mm with 0.6 mm width. The width of the feeding transmission lines ($W_f = 1.8 \text{ mm}$) is calculated to provide 50Ω impedance at both ends. The equivalent circuit of the 3-pole BPF can be performed as shown in Fig. 2. M_{12} and M_{23} denote the coupling coefficients between the adjacent resonators, and the cross coupling coefficient between the resonators 1 and 3 is represented by M_{13} . The external quality factors for the input and output couplings are represented by Q_{e1} and Q_{e3} , respectively. The angular frequency of resonator n is $\omega_{0n} = 2\pi f_{0n} = 1/\sqrt{L_n C_n}$ for $n = 1, 2$ and 3. To simplify the design, we can consider that $M_{12} = M_{23}$, $Q_{e1} = Q_{e3}$ and $\omega_{01} = \omega_{03}$.

Figure 1 Geometry of the proposed BPF

For the proposed filter, it can be seen that the cross-coupling between resonators R_1 and R_3 is positive ($M_{13} > 0$), and this

denotes that the attenuation pole of finite frequency is on the upper edge of the pass-band. The resonators (R_1 and R_3) are fed at an optimized point with a distance from the open-end (L_f) is 9.5 mm to provide the best external quality factor for the two-port network. The gap between the adjacent resonators is chosen to be 0.56 mm with optimal coupling coefficient, which leads to 100 MHz bandwidth for the bandpass filter.

Figure 2 Equivalent circuit of the 3-pole microstrip bandpass filter

The frequency performance is shown in Fig. 3. At the resonant 3.8 GHz frequency, the filter has a good return loss 25 dB for the targeted 5G spectrum and covers the 3.7 to 3.8 GHz band with a fractional bandwidth 3%. At resonance, the insertion loss has a minimum value of 0.9 dB as shown in Fig 3. Wide-stop bands of 3.8 GHz and 11 GHz are achieved for lower and upper edges of the passband, respectively, each with insertion loss with less than 10 dB. The selectivity of the passband bandwidth could be improved with a higher order filter by increasing the number of resonators. Fig. 4 elaborates the current distribution of the filter at the resonant frequency of 3.8 GHz, obtained using CST software: the electric field is mainly distributed at the first and third open-ended resonators, with maximum current density 50 A/m^2 at the edges of the adjacent resonators R_1 and R_3 . The next section discusses integrating the same designed bandpass filter with two varactor diodes and a proper biasing circuit to provide tunable characteristics.

Figure 3 Wide-band insertion/return loss performance for the proposed BPF

Figure 4 Simulated current distribution for the 3-pole bandpass filter

3 Design and Performance of the Tunable Bandpass Filter

Frequency reconfigurability or tunability is important for multi-band systems to cover the required variations. The use of varactors is a well-known technique for reconfigurable filters. Fig. 5 shows the geometry of such a proposed filter, including the biasing circuit required to tune the varactor diodes and two RF choke inductors to prevent the RF signal passing through the biasing circuit. To gain the reconfigurability property, two parasitic transmission lines are added to the three-pole filter. The length of the parasitic lines is chosen and optimised to be 10 mm, with 1.5 mm width, and the gap between these elements and the coupled-line resonators is 0.5 mm.

Figure 5 Geometry of the proposed tunable microstrip bandpass filter

Also, two inductors ($L_1 = L_2 = 10$ nH) are used as radio frequency (RF) chokes to limit and reduce RF leakage into the

biasing circuit and power leads: they act as open circuits to the RF signal at the ends of the switches. The optimized parameters are obtained using CST software. The co-simulation between CST MWS and CST DS for the designed reconfigurable filter is presented and achieved as shown in Fig. 6.

The simulation takes into account the spice model for the varactor diodes with the biasing circuit parameters. The manufacturer-specified parasitic inductances and capacitances of the packaging are included as well. The CST time domain solver uses 10 lines per wavelength as mesh density control parameter, and the filter dimensions are optimized for good matching over the tuning range. The biasing circuit controls both the resonant frequency and bandwidth characteristics. This filter uses the SMV1234 Skyworks Solutions varactor diode, size 1.5×0.7 mm². Increasing the reverse voltage widens the depletion region of the varactor, decreasing its capacitance, and vice versa as seen in Fig. 7. The filter's biasing circuit, with the SPICE model for the varactor, is modelled as shown in Fig. 8.

Figure 6 A hybrid EM-circuit co-simulation of the proposed reconfigurable filter with biasing circuit and SPICE models of the diodes

Figure 7 Typical capacitance-voltage characteristics of different Skyworks varactor diodes [26]

Figure 8 Biasing circuit for the proposed varactor diode

Next, the return and insertion losses of the filter are presented and discussed. The achieved results for the return loss shown in Fig. 9, indicate that different reverse bias voltages of the varactor between 0.5 V and 5.6 V, give capacitance values of 2.7, 3.3, 4.8, 6 and 8 pF, and alter the return losses in the 2.5 to 3.8 GHz range, between -17 dB and -30 dB. Fig. 10 shows the achieved insertion losses for the values corresponding to those of Fig. 9. Good insertion losses are obtained over the tuning range, of around 1 dB at the coverage bandwidth. The proposed planar filter is tunable with the resonant frequency. Nevertheless, the bandwidth is slightly altered with the tunable frequency. Fig. 11 shows a wide-band frequency response for the proposed tunable filter at the resonant frequency of 3.7 GHz. The performance presents a good stop-band characteristics for both lower and upper bands of the passband bandwidth. More than 10 GHz stopband has been achieved on the upper edge of the passband frequency with an insertion loss of less than 10 dB. Besides, three transmission zeros are successfully generated on the upper stopband bandwidth, which leads to a good out of band and selectivity characteristics. Figs 9-11 show that the proposed tunable filter can cover a wide tuning range from 2.5 to 3.8 GHz, indicating that the filter is promising and applicable for 4G and 5G wireless communication applications.

Figure 9 Performance of the return losses with different biasing voltages

Figure 10 Performance of the insertion losses with different biasing voltages

Figure 11 Wide-band performance of insertion/return losses for the proposed tunable filter

Table 1 compares the performance of this microstrip reconfigurable filter with other recent similar designs. The filter proposed here has a relatively good performance in respect of performance, size, number of switches and design complexity.

Table 1 performance comparison with some recent tunable filter designs

Ref.	f_0 (GHz)	BW (MHz)	No. of Switches	S_{11} (dB)	S_{21} (dB)	Filter Size (mm ³)
[21]	1.1-2.1	40	7	< -15	-6	52×12×1.5
[27]	1.7-2.9	40	7	-16	-4	36×35×0.8
[28]	0.76-2	75-290	2	< -15	-1.2	100×8×0.5
this work	2.5-3.8	100	2	< -15	-0.8	13×8×0.81

4 Conclusion

A design for a compact reconfigurable-microstrip bandpass filter with a wide tuning range properties is presented and discussed in this paper using a new hybrid simulation technique. CST software is used to simulate and optimize the design, with hybrid co-simulation between CST MWS and CST DS is used to implement the designed filter taking into account the SPICE model for the varactor diodes and the effect of the biasing circuit. The filter is reconfigurable in the resonant frequency, covering 2.5 to 3.8 GHz bandwidth under the control of two varactor diode switch. The filter covers both the 4G and sub-6 GHz 5G spectrum for possible application in stationary terminals of cognitive radio systems and other applications in future wireless communications. The proposed 3-pole coupled-line bandpass filter has a number of attractive properties, which include: (1) A very compact and simply structured. (2) Good stopband rejection and selectivity have achieved. (3) The measured insertion loss is very low with good return loss to cover the 4G (2.5-2.6 GHz) and 5G (3.4-3.8GHz) spectrum. (4) Compared to the designed filters in [6], [8], [10] and [20], the proposed filter has a smaller size and better performance with the merit of reconfigurable characteristics.

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