Design, Simulation and Implementation of Very Compact Open-loop Trisection BPF for 5G Communications

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Abstract—A very compact microstrip open-loop bandpass filter (BPF) with asymmetric frequency response and covering the 3.4 to 3.7 GHz 5G spectrum is presented in this paper. The planar BPF consists of three trisection open-loop ring resonators with 50 Ω transmission lines for input and output terminals. An attenuation zero of finite frequency is successfully generated on the upper edge of the passband to achieve sharper cut-off frequency for the passband. The realization of the microstrip trisection filters not only reduces the size of the layout but also introduces either positive or negative cross-coupling. The cross-coupling coefficients (Mij) between the poles are optimized to operate at the sub-6 GHz 5G spectrum with appropriate impedance bandwidth. The illustrated BPF is modeled and analyzed using computer simulation technology (CST) tool and is fabricated on a Rogers RO3010 substrate with a relative dielectric constant (εr) of 10.2 and a very small size of 9.5×6×1.27 mm3. The simulated and measured results show a good agreement.

Keywords — microstrip, BPF, 5G, trisection, RO3010, computer simulation technology.

I. INTRODUCTION

Radio frequency (RF) interference is a serious issue in modern systems of microwave (MW) channels such as in green RF and wideband satellite communications [1-6]. Planar bandpass BPFs are generally used to suppress unwanted noise signals in many wireless systems [7], mainly in RF and MW applications because of their efficient 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 millimeter-wave band (26 GHz) [8]. BPF is used in different 5G applications for rejecting noise frequencies [9,10]. A BPF consists of a number of poles, and the designs of the resonators and the number of resonators define the filter properties. Most planer filter miniaturization techniques try to minimize and optimize these parameters [11-18]. Many approaches and structures have been presented such as Stepped-impedance resonators (SIR), combline, ring resonators, parallel-coupled lines, and stub impedance resonators [19-24]. A microstrip design with Chebyshev properties is introduced in [19] to operate at 2.4 GHz with a ripple factor of 0.55. The achieved insertion and return losses were better than 1 dB and 12 dB, respectively. Another compact microstrip bandpass filter was presented by using a new transmission combline technique [20]. In this structure, two microstrip lines of three parallel-coupled resonators, λ/4 long, was introduced to produce a BPF with a resonant frequency of 3 GHz. Non-Uniform units are presented between the two microstrips, and the overall area of the filter was 20×7 mm2. In [21], a different approach was presented by using a low temperature co-fired ceramic (LTCC) design, whose implementation was achieved by investigating the reliable electromagnetic field, leading to proper BPFs with small layouts. In [22], hairpin designs were considered to implement a microstrip BPFs with low losses and small sizes. Modeling of these filters produces a non-constant mutual coupling between the poles of the filter with a T-shaped feeding technique. In addition, the practical results of the s-parameter show a shift of roughly about 0.4 GHz related to the theoretical one. For this BPF design, the operation frequency of 5.7 GHz is considered to be used for RFID applications with a compact dimension of 25×11.5 mm2. Other compact designs were presented in [23, 24] with coupled-line resonators which are providing a very low loss to be used for modern RF systems. A new microstrip coupled line filter is presented in [23]. The filter has two resonators and designed with a compact size of 27.2×6 mm2, with two transmission zeros are introduced to improve the roll-off factor. The filter works on a 1.45 GHz frequency with 13 % fractional bandwidth, 3 dB insertion loss and 18.5 dB return loss were achieved. In [24], a modified stepped-impedance (SIRs) is proposed and implemented using the coupled line technique. Compared to other resonators, the proposed structure here has the property of less number of vias, making this design has a vital in the multi-layer structures. The same structure adopted to 4th poles design, leading to a reduced insertion and return loss to 1.5 dB and less than 20 dB, respectively, by employing an overall size of about 13×11 mm2.

On top of that, many RF systems require filters with a high roll-off on only one side of the transmission band, but less or
none on the other side. Thus, introducing a microstrip filter with asymmetric s-parameter characteristics will be essential because these designs require a high number of poles, resulting in a high insertion loss, non-compact and pricy structures.

Our paper proposes a very compact trisection open-loop ring resonator BPF with asymmetric frequency characteristics, simulated by CST to cover the 3.4 to 3.7 GHz spectrum for the sub-6GHz 5G applications. The introduced three-pole open-loop resonator filter is fabricated on a Rogers RO3010 substrate with a relative dielectric constant of 10.2 and a very compact size of 9.5×6×1.27 mm$^3$. Moreover, it is important to say that this structure can be simply adapted to provide the tenability property and could be simply integrated with antenna design, to tackle the so-called “filtenna”. The presented microstrip filter and its theoretical and practical performance are studied and discussed in the next texts.

II. MICROSTRIP 3-POLE OPEN-LOOP FILTER DESIGN AND IMPLEMENTATION

The design steps of the reported BPF can be summarized with the following procedure:

Step 1) Design a low-pass filter (LPF) prototype with normalized characteristics impedance ($g_0$) and cut-off frequency ($\Omega_c$).

Step 2) Using some transformation techniques to convert the designed low-pass filter prototype to the band-pass filter operating on the required resonant frequency. This step will result in a band-pass filter with a lumped-element circuit consists of capacitors and inductors.

Step 3) Richards’ transformation can be applied to transform the band-pass filter into a microstrip planer band-pass filter.

A. Low-Pass Filter (LPF) Prototype

A 3-pole lumped element low-pass filter (LPF) prototype is designed on this sub-section. The structure is operating on 3.6 GHz with FBW 11% and low ripple factor. The equivalent circuit of the prototype design with order $n$ is shown in Fig. 1 with LPF prototype parameters $g_i$ for $i=0$ to $n+1$. According to [2], the LPF with Butterworth properties can be used to compute the values of $g_i$ to give: $g_0 = g_4 = 1 \Omega$, $g_1 = g_3 = 1 \Omega$, and $g_2 = 2 \Omega$ for resonance frequency $\Omega_c = 1 \text{rad/s}$.

Fig. 1. RLC equivalent circuit of the prototype LPF.

B. Lumped Element BPF Design and Analysis

Frequency and element transformation techniques can be used to obtain the equivalent circuit of the BPF from the LPF prototype which has a normalized characteristic impedance $g_0 = 1$ and $\Omega_c = 1.0 \text{rad/s}$. The angular frequency conversion affects just the reactive components and has no effect on the resistive ones. The resonance frequency and the impedance scaling factor are $2\pi \times 3.6 \times 10^9 \text{rad/s}$ and $\gamma_0 = 50$ respectively. From [2], we find $L_1 = L_3 = 22 \mu H$, $L_2 = 0.15 \mu H$, $C_1 = C_3 = 0.1 \text{pF}$ and $C_2 = 18 \text{pF}$. As a result, and according to the procedure detailed above, we can get the equivalent circuit of the lumped-element BPF as shown in Fig. 2.

According to [7], Richards’ transformations are applied to convert the designed lumped-element BPF designed into a transmission line model.

The geometry of the proposed cross-coupled BPF is shown in Fig. 4. Three open-loop ring-resonators fed by two ports 50 $\Omega$ input impedance minimize the physical size, eliminating the need for vias. The filter has a transmission line feed and uses Rogers RO3010 substrate, with $h = 1.27 \text{mm}$, $\varepsilon_r = 10.2$ and loss tangent = 0.0022. The resonant frequency 3 of 6GHz is chosen as it is suitable for 5G.

The equivalent circuit of the trisection open-loop BPF can be performed as shown in Fig. 5. $M_{12}$ 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 $Q_{eo}$, respectively. The angular frequency of resonator $n$ is $\omega_{on} = 2\pi f_{on} = 1/\sqrt{(Z_n C_n)}$ for $n = 1, 2$ and 3. To simplify the design, we can consider that $M_{12} = M_{23}$, $Q_{e1} = Q_{e3}$ and $\omega_{o1} = \omega_{o3}$. For the proposed filter, it can be seen the cross-coupling between resonators 1 and 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 physical parameters of the planar 3-pole filter can be calculated by employing the same design steps detailed in [20]. The configuration of the BPF filter and its optimized parameters are shown in Fig. 4 and Table 1, respectively. In addition, the dimensions of the proposed BPF is about $0.27 \lambda_{g0} \times 0.17 \lambda_{g0}$, where $\lambda_{g0}$ represents the guided wavelength of a 50 $\Omega$ transmission line on the substrate at the resonance frequency. Obviously, the size of the designed filter is very compact. The optimized parameters are obtained by using the trust region framework algorithm embedded with the CST software as detailed in Table 1. The proposed 3-pole cross-coupled bandpass filter has a number of attractive properties, which include: (1) The proposed design is very compact in size and simply structured. (2) Good stopband rejection and selectivity have achieved. (3) The measured insertion loss is very low with good return loss and group delay to cover the mid-band of 5G spectrum (3.4-3.7GHz).

### Table 1. Geometric dimensions (in mm) of the proposed 3-pole open-loop planar filter.

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### III. SIMULATION AND MEASUREMENT PERFORMANCE OF THE PROPOSED FILTER

In this section, the performance of the proposed trisection microstrip BPF filter is studied. Fig. 6 shows the simulated results of the return loss and the insertion loss of the designed 3-pole BPF. The simulation results show that the proposed filter has an insertion loss of 0.8 dB across the pass-band with return loss better than 30 dB. Moreover, and to increase the selectivity of the pass-band, two transmission zeros have been successfully generated in the upper edge of the pass-band.

Fig. 7 shows the measured results of the return/insertion losses and prototype photo of the fabricated 3-pole open-loop BPF. The measured results show that the implemented BPF is resonating at 3.55 GHz with -3 dB FBW of 8%. The attenuation characteristics for the fabricated BPF filter show more than 20 dB filters up to 6.8 GHz on the higher edge of the passband and a stop-band from 0 Hz to 3 GHz with an insertion loss of less than -10 dB can be achieved. At the resonant frequency, the measured insertion and return losses for the fabricated BPF filter are less than 0.9 dB and greater than 22 dB, respectively.
The simulation results achieved by CST software and the measurements from the vector network analyzer (HP 8510C) show good agreement. Fig. 8 shows the frequency response of the group delay and the phase of S21 for the designed bandpass filter. The maximum in-band group-delay (τg) variation around 1ns for the proposed filter. Table 2 compares this proposed microstrip open-loop BPF with other BPF designed recently with similar configurations and performances. The BPF proposed here has a good performance compared with the others with respect to the filter response, size and design complexity.

Fig. 8. Group delay and phase of S21 for the designed trisection BPF.

Table 2. Performance comparison with some other designs.

| Ref.  | f0 (GHz) | BW (MHz) | |S11| (dB) | |S21| (dB) | Size (λg0×λg0) |
|-------|----------|----------|--------|--------|--------|----------------|-----------------|
| [19]  | 2.45     | 100      | 18     | 1      | 1.1×0.3 |
| [20]  | 3        | 1500     | 11     | 1      | 0.7×0.2 |
| [22]  | 5.1      | 500      | 28     | 1.1    | 1.6×0.31 |
| [29]  | 2.5      | 100      | 19     | 1.2    | 0.31×0.1 |
| this work | 3.5 | 300 | 22  | 0.9 | 0.27×0.17 |

IV. CONCLUSIONS

A structure for a very compact 3-pole open-loop planar BPF is proposed, fabricated and measured in this article with asymmetric frequency characteristics and operating in the 3.4 to 3.7 GHz spectrum for 5G wireless communications. to improve the stop-band performance of the designed BPF, one transmission zero with finite frequency is successfully generated on the upper side of the passband. The practical results are in good agreement with the theoretical one.

ACKNOWLEDGEMENT

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement H2020-MSCA-ITN-2016 SECRET-722424.


