Design of a Compact Microstrip Triple Independently Controlled Pass Bands Filter for GSM, GPS and WiFi Applications

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ABSTRACT An ultra-compact triple-band bandpass filter based on dual-mode quarter-wave resonator for GSM, GPS, and WiFi applications is presented in this study. The filter consists of three quarter-wave resonators assisting in controlling each passband independently. The first operating frequency band is obtained by the direct-feed resonator which acts as a source to load coupling for the inner two resonators which are operating at higher frequency bands. The outermost resonator is coupled to the inner loaded resonators, thus a pair of transmission zeros between each passband can be excited and hence high-frequency selectivity can be obtained. To miniaturize the overall size of the filter, all resonators are folded and are jointly connected through a common metallic via with the ground. The design has a symmetric structure therefore, even-odd mode analysis method is applied to obtain the three controllable operating frequency bands. The first operating band is centered at 850 MHz which caters for GSM applications, while the second and third frequency bands centered at 1.57 GHz and 2.4 GHz fall in the GPS and WiFi wireless applications. The filter with an ultra-compact size of 0.10\(\lambda_g\) \times 0.09\(\lambda_g\) (0.009\(\lambda_g^2\)) despite feed lines (\(\lambda_g\) is the waveguide length centered at 850 MHz) is designed, fabricated and measured for the purpose of validation. Both the simulated and measured results are in good agreement and endorse the design concept.

INDEX TERMS Tri-band filter, quarter-wavelength resonator, microstrip BPF filter, transmission zeros, wireless applications.

I. INTRODUCTION

With the fast-growth in modern wireless communication technology to support various communication modes at different frequency bands such as GNSS (Global Navigation Satellite System), GSM (Global System for Mobile Communications), WLAN, ISM, and RFID into a single unit is a challenging job for microwave researchers. For the said applications, multiband bandpass filters (BPFs) are the indispensable components for integrating with different communication modes into one device without interference. Due to their suitability of planar structure, low cost, small size and ease of fabrication [1]–[6] these filters are designed for various applications. So, in this regard, many studies have been published in recent years to design a miniaturized dual and triple-band (BPFs) based on different techniques such as stub loaded resonators (SLRs), embedded stub loaded resonators, ring resonators, multimode resonators and step impedance resonators (SIRs) etc [7]–[33].

A dual-band filter based on quadruple mode square ring resonators is designed and fabricated in [7], consisting of two square ring resonators and two open-circuited stubs attached on either side of the square rings. The proposed resonator structure is not fully symmetric therefore it is difficult to design high-order dual-band filters with the desired passbands. The structure size also increases while using two resonators. A dual-band filter based on dumbbell-shaped and quad-mode SLR is presented in [8], [9]. The attractive feature...
of these designs is good differential-mode transmission but poor common-mode suppression and larger circuit area due to loaded multiple resonators are the major drawbacks. To overcome these limitations, the authors of [10]–[12] designed dual-band filters using multimode resonators such as multimode slotted line and embedded coupled resonators, but multilayer process and complex structure lead to the high fabrication cost.

A combo of dual-band filters along with tri-band filters was also reported in [13]–[16]. In [13], dual and triband filters using triple mode SLRs are designed and fabricated. The presented filters have good fractional bandwidth, but large circuit size is a major drawback associated with the designs utilizing more than one resonator. Also, the selectivity of the filter is very poor having only two transmission zeros (TZs) between the passbands. The authors of [14], [15], designed dual and triband BPFs based on quintuple and Penta-mode resonators. The fabricated filters have the drawbacks of poor selectivity, poor insertion losses and larger circuit size. To improve the passband insertion losses, a T-shaped SLR was used to first design a dual-band filter at the resonance frequency of 2.4 GHz and 4.48 GHz, and then by embedding asymmetrical coupled lines to the feed lines to produce another band at 3.58 GHz in order to achieve a compact triband response. The design has good 3dB absolute bandwidth but the 3dB roll-off skirts and larger circuit area are still a major drawback related to that design.

In [17], a triband filter based on dual-mode SLRs was designed and fabricated on Rogers-RO5880TM substrate for GPS, WLAN and WiMAX applications. The filter has the advantage of exciting five TZs on either edge of the passbands, however, the circuit suffers a larger circuit area. To improve the 3-dB roll-off skirts, a filter with eight TZs based on defected ground structure array was designed and fabricated in [18], for WiMAX, WLAN and LTE applications. The proposed model has the advantage of high selectivity but low fractional bandwidth, circuit complexity, poor passbands insertion loss and larger circuit area were a major shortcoming of that design. To further improve the passband isolation, another tri-band filter using three types of resonators was designed and fabricated in [19]. The proposed filter is a combination of SIR, square split ring resonator, and step impedance SLR to obtain the desired frequency bands for Bluetooth, WiMAX and WLAN applications. Ten TZs were excited which leads the design to high selectivity but a solution for filter miniaturization is still to be achieved. A novel triband filter using high-temperature superconducting material is modelled in [20], for GSM, WLAN, and WiMAX applications, where three single-band filters are combined to design a tri-band filter. The filter has good insertion losses and all the bands are independently controlled. But the circuit size is greatly increased because of using three single-band filters. Also, the filter is packed in a gold-plated box which increases the fabrication cost. Another triple-band filter using a multilayer structure is presented in [21]. The presented filter has poor fractional bandwidth, high insertion losses, larger circuit size and a multilayer structure leaves the fabrication process more complex. To improve the fractional bandwidth and insertion loss for the passbands, the authors of [22]–[25], designed a triple-band BPFs based on uniform SIRs and open stub loaded SIRs for different frequency bands. But structural complexity and larger circuit dimensions were major drawbacks associated with these designs. A novel compact triple-band BPF using the right- and left-handed resonators was modelled in [26]. The proposed filter has good selectivity in passbands, but poor insertion losses were a major drawback which came with this design. Moreover, the insertion losses for the first and third operating band were greater than 3dB, which is highly discouraged in this field of research. A triband filter based on symmetrical and multipath SLRs for different wireless applications is presented in [27], [28]. The published designs have low insertion losses and high selectivity, but poor fractional bandwidth and larger circuit dimensions were the major drawbacks associated with these designs. Recently a triband response is achieved in [29], using ring multimode resonators at frequencies of 1.2/2.1/3.1 GHz, respectively. The presented filter has poor selectivity by exciting only four transmission zeros in the passbands. To miniaturize the structure dimension, resonators were folded but still there exists a room for improvement in size reduction. To control all the frequency bands independently, the authors of [30], designed a new compact triband filter based on embedded resonators for WiFi and WiMAX applications. The proposed design has good selectivity but low fractional bandwidth, high passband insertion losses and larger circuit area; as the limitations of the design. In [31], a tri/quad-band BPFs based on slotted feed lines are designed and fabricated. The important feature of that design is high selectivity and controllable bandwidth, but poor passband insertion losses, especially for second and third frequency bands, where the losses are greater than 3dB. Moreover, circuit complexity is also a major limitation of the work. A new class of miniaturized triband filters using Hexamode SIR is proposed in [32]. The presented work has high isolation between the passing bands. However, the design suffers from large circuit dimensions and poor fractional bandwidth. The authors of [33] modelled a triband response using shorted SLR and quarter-wave uniform SIR. The first and second band were created using shorted SLR and controllable harmonic while the third frequency band was excited using uniform quarter wavelength SIR. The most important advantage of that design is the three coupling paths which independently controlled the bandwidth of all passing bands. But the drawbacks are the low fractional bandwidth and poor selectivity. Moreover, the design also covers a larger circuit area. As a conclusion to the above discussion, designing an ultra-compact and high selectivity triple-band BPF for the handheld applications is still a challenging task for the researchers in the field of microwave filter design.

The motivation behind this study is to bring forward a state-of-the-art triple-band bandpass microwave filter with miniaturized size and controllable passbands for GSM, GPS, and WiFi applications. The proposed filter design is based on
T-shaped dual-mode quarter-wavelength resonator. The first operating band is obtained by the direct-feed resonator which acts as a source to load coupling for the inner two resonators which are operating at higher frequency bands. The coupling between the resonators generates a pair of transmission zeros between each passband and hence high-frequency selectivity is obtained. To reduce the overall size of a filter, all resonators are bent and relate to a common metallic hole connection to the ground. The main advantage of this design is that all TZs can be controlled without altering the central frequencies, this phenomenon will be proved later in the paper. The design has a symmetric structure, therefore, the even-odd mode analysis method is applied to obtain the three operating bands i.e. 850 MHz/1.57 GHz/2.4 GHz for GSM, GPS, and WiFi applications. The filter was designed, fabricated and measured for the purpose of authentication. The simulated results are well-matched with the measured results.

II. QUARTER WAVELENGTH RESONATOR ANALYSIS

The proposed filter design is based on T-shaped dual-mode quarter-wavelength resonators, where each resonator is comprised of two open-ended stubs and one shorted stub as shown in Fig.1. From the given figure, the admittance of the open-circuited transmission line is \( Y_1 \) having length \( L_1 \), while the admittance of short-circuited line is \( Y_2 \) having length \( L_2 \). The design has a symmetric structure about A-A’, therefore, even-odd mode analysis method is applied to predict the three controllable operating bands. The first, second and third passbands are designed through resonator “A”, “B”, and “C” respectively, and the corresponding equivalent odd and even mode circuits are shown in Fig. 2 (a-f), while the proposed filter topology is depicted in Fig. 3. Moreover, the resonator “A” acts as a direct feed resonator and provides a source to load coupling for the inner two resonators which are operating at higher bands. Reference to the basic microwave circuit theory [34], the equation for the characteristic input admittance of the resonator “A” can be calculated and is given by:

\[
Y_{in} = Y_0 \frac{Y_{L} + jY_0 \tan \theta}{Y_0 + jY_L \tan \theta}
\]  

(1)

where \( \beta = \frac{2\pi}{\lambda_g} \) is the propagation constant, \( \lambda_g \) is the guided wavelength, and \( L \) is the electrical length of the stubs. Here \( \theta = \pi/2 \) for \( \lambda/4 \) transmission line. For resonator “A” the first even mode input admittance \( Y_{in, even1} \) and the resonance frequency \( f_{even1} \) can be calculated by taking the stub length \( L_{16} \) shorted thus, \( Y_L = \alpha \) and \( Y_0 = (\frac{4\alpha}{2}) \). So, the above equation becomes:

\[
Y_{in, shorted} = -j(Y_{16} \cot \frac{\theta}{2})
\]  

(3)

where \( Y_{in, shorted} \) is the input admittance of the shorted stub having length \( L_{16} \). By putting the value of \( Y_{in, shorted} \) and \( Y_0 = Y_1 \) in equation (1) and using Fig. 2(a), we get the equation of \( Y_{in, even1} \) as,

\[
Y_{in, even1} = -jY_1 \frac{Y_{16} - 2Y_1 \tan(\theta_1 + \theta_2 + \theta_3 + \theta_4 \cdot \tan(\theta_{16}))}{2Y_1 \tan(\theta_{16}) + Y_{16} \tan(\theta_1 + \theta_2 + \theta_3 + \theta_4)}
\]  

(4)
where $\theta_1 = \beta L_1$, $\theta_2 = \beta L_2$, $\theta_3 = \beta L_3$, $\theta_{4/2} = \beta L_{4/2}$, $\theta_{16} = \beta L_{16}$, and $Y_1 = \ldots$ respectively. At resonance $Y_{in,even} = 0$, so, the corresponding equation for the first even-mode $f_{even1}$ fundamental frequency is,

$$f_{even1} = \frac{2(2n - 1)c}{4(L_1 + L_2 + L_3 + L_{4/2} + L_{16})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (5)$$

where $c = 3 \times 10^8$ m/sec is the speed of light, $n = 1, 2, 3, \ldots$, and is the effective permittivity of the Roger RO-4350 substrate which is given by:

$$\varepsilon_{eff} = \frac{1 + \varepsilon_r + \varepsilon_r - 1}{2} \times \frac{1}{\sqrt{1 + \frac{12\varepsilon_r}{w}}}$$  \hspace{1cm} (6)$$

where is the relative permittivity, $w$ and $h$ are the width and height of the substrate material. Similarly, for odd-mode, the transmission line is shorted at symmetry therefore, by placing $Y_0 = Y_1$ and $Y_L = \infty$ in equation (1) and using Fig. 2(b) to get the input admittance $Y_{in,odd1}$ which is given below:

$$Y_{in,odd1} = \frac{Y_1}{j\tan(\theta_1 + \theta_2 + \theta_3 + \theta_4)}$$  \hspace{1cm} (7)$$

Again, at resonance $Y_{in,odd1} = 0$ therefore, the equation for the first odd-mode resonant frequency becomes:

$$f_{odd1} = \frac{2(2n - 1)c}{4(L_1 + L_2 + L_3 + L_{4/2})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (8)$$

Using the same procedure, the equations for the even-odd mode resonance frequencies of the resonator “B” and “C” can be calculated with the help of Fig. 2(c-f) and the basic microwave theory equations as given below:

$$Y_{in,even2} = -jY_2 \frac{Y_1 - Y_2 \tan(\theta_6 + \theta_7 + \theta_8 + \theta_9) \tan(\theta_{13})}{Y_1 \tan(\theta_{13}) + Y_2 \tan(\theta_6 + \theta_7 + \theta_8 + \theta_9)}$$  \hspace{1cm} (9)$$

$$f_{even2} = \frac{2(2n - 1)c}{4(L_6 + L_7 + L_8 + L_{5/2} + L_{13})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (10)$$

$$f_{odd2} = \frac{2(2n - 1)c}{4(L_6 + L_7 + L_8 + L_{5/2})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (11)$$

$$f_{even3} = \frac{2(2n - 1)c}{4(L_9/2 + L_{10} + L_{11} + L_{14} + L_{15})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (12)$$

$$f_{odd3} = \frac{2(2n - 1)c}{4(L_{9/2} + L_{10} + L_{11} + L_{15})\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (13)$$

Based on these equations, the passband resonance frequencies for the GSM, GPS, and WiFi wireless applications can be obtained and is proven in the later section of the paper.

### III. TRIBAND FILTER GEOMETRY

Based on the above geometrical analysis, an ultra-compact tri-band BPF is designed in 3D electromagnetic (EM) simulator ANSYS HFSS-15 and fabricated on Rogers RO-4350 substrate having thickness 0.762mm, tangent loss 0.004, and relative permittivity 3.66, respectively. The filter consists of three symmetrical dual-mode quarter-wavelength resonators. To reduce the circuit size of a filter, all resonators are folded and relate to a common metallic hole connection to ground. The proposed triband topology is shown in Fig. 3, while its geometrical parameters are listed in Table 1. The fabricated filter has an area of $22 \times 21$ mm². 0.10 $\lambda_g \times 0.09$ $\lambda_g$ (0.009 $\lambda_g$) despite feed lines and tested on Agilent E5071C network analyzer.

### IV. MATHEMATICAL DESIGN FOR FINDING THE RESONANT FREQUENCIES

The physical length of each resonator for the proposed triband filter is designed according to the above mathematical procedure. Based on this mathematics, the resonant frequencies of each passband have been calculated. The first passband is controlled through resonator A. As we know that the proposed filter is designed on a $\lambda/4$ transmission line therefore, each passband has two modes one is even, and one is odd. By placing the corresponding length values from Table 1 in equation (5) and using Fig. 2(a), the central frequency of the first even mode is obtained, which is 0.90 GHz. Now odd mode resonance frequency is calculated using equation (8) and Fig. 2(b) which is 0.86 GHz. Similarly, the fundamental even and odd resonant frequencies for the second and third passbands are calculated using equations (10-13) and Fig 2(c-f), i.e. $f_{even2} = 1.53$ GHz, $f_{odd2} = 1.57$ GHz, $f_{even3} = 2.4$ GHz, and $f_{odd,3} = 2.32$ GHz respectively. The slight shift in frequencies is due to the magnetic coupling between the resonators and they are adjusted to our desired band applications by performing parametric analysis in HFSS software.

### V. RESULTS AND DISCUSSION

A very compact triband filter based on dual-mode T-shaped $\lambda/4$ resonator is designed in this study. Three resonators are used to get a triband response. The first passband is obtained through resonator A which acts as a feeding structure for the inner resonators that are operating at higher bands. As shown in Fig. 4(a), the first passband is controlled through the length $L_3$ and by varying the length from 11 mm to 12 mm will shift only the first passband from GSM-850 to GSM-900 and it does not have any effect on the remaining bands. The second passband is obtained through resonator B and the control is shown in Fig 4(b). It is observed that the second band is controlled through length $L_6$ and by varying, it will tune down only the second passband while the first and third bands will remain fixed. The third band is controlled through resonator C and by changing the length $L_{10}$ it will affect only the third passband without affecting the other two bands. The control
is shown in Fig 4(c). Thus, it is verified that the proposed filter has the capability to control all the bands independently.

The second advantage is the control of transmission zeros according to the desired stopband frequency on each side of the passbands. As depicted in Fig. 5, by changing the parameter $t_1$ will influence only the position of transmission zeros without altering the fundamental resonant frequencies. This property will make the proposed filter superior from any other filters reported in the literature. As shown in Fig. 5, six transmission zeros are introduced by the following method. TZ2 and TZ4 are produced due to the electric coupling between the two symmetrical open-circuited stubs as denoted by $(L_3, w_1)$ or by gap $G_1$, TZ1 and TZ5 are generated by the source to load coupling while TZ6 is due to the diameter of via. TZ3 is the inherent transmission zero of the resonator.

Now calculate the external quality factor “Q_{ext}” and the coupling coefficient “$K_e$” using the following equations [36]:

$$K_e = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$  \hspace{1cm} (14)

$$Q_{ext} = \frac{f_c}{B.W_{3dB}}$$  \hspace{1cm} (15)

where $f_2$ and $f_1$ show the upper and lower frequency, $f_c$ represents the central frequency and $B.W_{3dB}$ represents the 3dB absolute bandwidth centred at $f_c$. The external quality factor can be determined between the outer resonator and the feedlines while the coupling coefficient can be determined by the coupling between the two resonators. When the gap between the two resonators increases, the coupling coefficient decreases while the external quality factor increases, as shown in Fig. 7-9 [37]. Fig. 6 shows the plot between $Q_{ext}$ and $t_1$, when parameter $t_1$ increases from 0.5 mm to
0.9 mm, the $Q_{ext}$ also increases according to equation (15). Fig. 7-9 shows the plots between $Q_{ext}$ and $K_e$ against $G_1$, $d_1$, and $d_2$ respectively. This shows that when the gap between the two resonators increases, the external quality factor increases while the coupling coefficient decreases according to equation (14) and (15).

VI. SIMULATION AND FABRICATION RESULTS

To validate the proposed structure, a miniaturized triple-band BPF is designed and fabricated. The proposed filter is designed in the following manner. First, a prototype is designed in 3D electromagnetic (EM) simulator ANSYS HFSS-15 and then the parametric analysis is performed in order to achieve the desired triband response, then it is fabricated on Rogers RO-4350 substrate having thickness 0.762mm, tangent loss 0.004, and relative permittivity is 3.66 and the tool used to fabricate the PCB is LPKF S63 Protolaser. After that, the fabricated design is tested using the Agilent E5071C network analyzer device for the purpose of authentication. In Fig. 10, good matching can be seen between the measured results and simulated results. The ripples in frequency response are due to fabrication tolerance.

| Ref | Freq. Bands (GHz) | IL (dB) | 3-dB FBW (%) | Circuit size (mm) | TZ s |
|-----|-------------------|---------|--------------|------------------|------|
| 13  | 2.50/3.68/5.04   | 0.24/0.33/0.40 | 16.7/14.4/13.2 | 0.31/0.32       | 3    |
| 14  | 2.35/3.44/5.2    | 1.1/2.2/3 | 20.8/7.7/11.1 | 5               | 0.22/0.21 | 2   |
| 15  | 2.48/3.58/4.4/8  | 0.6/0.3/1.01 | 10/12/8/5   | 0.26/0.23       | 3    |
| 17  | 1.75/2.43/3.45   | 0.74/1.14/0.35 | NA          | 0.44/0.56       | 5    |
| 18  | 2.43/4.55        | 1.2/1.9/2.02 | 5.33/3.45   | 0.24/0.21       | 8    |
| 20  | 1.82/4.35        | 0.07/0.08/0.1  | 4/4/1/4     | 0.49/0.32       | 3    |
| 21  | 5.44/6.98/8.37/6 | 1.9/1.7/2   | 6/6/2.9     | 0.16/0.34       | 4    |
| 23  | 1.82/4.35        | 1.2/1.8/2.1  | 7.8/3.7/2.9 | 0.23/0.20       | 6    |
| 24  | 1.39/2.63/3.5    | 1.5/0.6/1.33 | 5/11/3      | 0.56/0.77       | 5    |
| 25  | 0.92/4.55        | 0.64/0.68/1.4 | 23/10/17   | 0.13/0.16       | 4    |
| 28  | 1.75/1.82/4.1    | 0.7/0.69/0.9 | 6.1/3.5/3.1 | 0.21/0.12       | 6    |
| 29  | 1.21/2.16/3.1    | 0.8/0.9/1.2  | NA          | 0.14/0.20       | 4    |
| 30  | 2.43/5.13        | 1.6/1.6/1   | 6/5/7       | 0.23/0.19       | 6    |
| 32  | 1.93/3.35/5.8    | 0.94/1.21/1.9 | 4.74/8.61/2.7 | 0.19/0.23   | 5    |
| 33  | 1.52/3.5        | 0.34/0.76/1.0 | 5/7/6      | 0.202/0.2       | 4    |
| 35  | 0.98/1.57/1.8    | 0.9/1.7/0.8  | NA          | 0.21/0.15       | 6    |

This Work: 0.85/1.57/2.4 | 0.98/1.1/0.96 | 16.84/5.5/9.6 | 0.10/0.09 | 6    | 77161
Two 50-Ω feedlines are used as an input/output port and are connected on both sides of the filter. The presented prototype consists of three λ/4 resonators A, B, and C to control the three passbands independently. The first operating band is obtained by the direct-feed resonator which acts as a source to load coupling for the inner two resonators. The second passband is obtained through resonator B while the third band is obtained through resonator C. The operating fundamental resonance frequencies of the proposed triband filter are 850 MHz, 1.57 GHz, and 2.4 GHz for GSM-850, GPS, and WiFi wireless applications. The corresponding 3dB absolute fractional bandwidth is 16.84%, 3.5%, and 9.6% and the measured in-band return loss is greater than $-15$ dB for each passband. The insertion losses (IL) are 0.98 dB, 1.1 dB, and 0.96 dB at GSM-850, GPS, and WiFi frequency bands. To increase the 3dB roll-off skirts and stopband performance of the filter, six transmission zeros were generated at 1.04 GHz, 1.16 GHz, 1.82 GHz, 2.22 GHz, 2.56 GHz, and 3 GHz respectively. A comparison of this filter with some published state of the art designs in terms of insertion loss, fractional bandwidth, transmission zeros and circuit size are listed in Table 2. This shows that the proposed filter has a compact size and good electrical performance in wireless applications.

VII. CONCLUSION

In this manuscript, a miniaturized BPF with three passbands using symmetric dual-mode λ/4 resonator is presented and analyzed for GSM (850 MHz), GPS (1.57 GHz), and WiFi (2.4 GHz) wireless applications. To realize the triband response, three quarter wavelength resonators (A, B, and C) are used to obtain the three controllable frequencies with 3-dB FBW of 16.84%, 3.5%, and 9.6% respectively. The overall circuit size of the filter is $22 \times 21$mm$^2$ (0.10 $\lambda_g \times 0.09$ $\lambda_g$) irrespective of the feedline. Finally, the design has been fabricated and measured in order to compare the simulated results with measured results. Thus, the proposed triband filter has good potential for integration in the existing modern multiband wireless applications.

REFERENCES

[1] R. Karimzadeh-Jazi, M. A. Honarvar, and F. Khajeh-Khalili, “High Q-factor narrow-band bandpass filter using cylindrical dielectric resonators for X-band applications,” Prog. Electromagn. Res. Lett., vol. 77, pp. 65–71, Sep. 2018, doi:10.2528/PIERL18041007.

[2] R. Kumar and S. N. Singh, “Design and analysis of ridge substrate integrated waveguide bandpass filter with octagonal complementary split ring resonator for suppression of higher order harmonics,” Prog. Electromagn. Res., vol. 89, pp. 87–99, 2019, doi:10.2528/PIER18080404.

[3] A. K. Gorur, “A novel compact microstrip balun bandpass filter design using interdigital capacitor loaded open loop resonators,” Prog. Electromagn. Res., vol. 76, pp. 47–53, 2018, doi:10.2528/PIER18010926.

[4] F. Wei, H. J. Yue, X. H. Zhang, and X.-W. Shi, “A balanced quad-band BPF with independently controllable frequencies and high selectivity,” IEEE Access, vol. 7, pp. 110316–110322, 2019.

[5] Q. Yang, Y.-C. Jiao, and Z. Zhang, “Compact multiband bandpass filter using low-pass filter combined with open stub-loaded shunted stub,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 4, pp. 1926–1938, Apr. 2018.

[6] F. Khajeh-Khalili and M. A. Honarvar, “A design of triple lines wilkinson power divider for application in wireless communication systems,” J. Electromagn. Waves Appl., vol. 30, no. 16, pp. 2110–2124, Nov. 2016.

[7] B. Ren, H. Liu, Z. Ma, M. Ohira, P. Wen, X. Wang, and X. Guan, “Compact dual-band differential bandpass filter using quadmode stepped-impedance square ring loaded resonators,” IEEE Access, vol. 6, pp. 21850–21858, 2018.

[8] L.-H. Zhou, Y.-L. Ma, J. Shi, J.-X. Chen, and W. Che, “Differential dual-band bandpass filter with tunable lower band using embedded DGS unit for common-mode suppression,” IEEE Trans. Microw. Theory Techn., vol. 64, no. 12, pp. 4183–4191, Dec. 2016.

[9] L.-H. Zhou and J.-X. Chen, “Differential dual-band filters with flexible frequency tuning using asymmetrical shunt branches for wideband CM suppression,” IEEE Trans. Microw. Theory Techn., vol. 65, no. 11, pp. 4606–4615, Nov. 2017.

[10] X. Guo, L. Zhu, and W. Wu, “Balanced wideband/dual-band BPFs on a hybrid multimode resonator with intrinsic common-mode rejection,” IEEE Trans. Microw. Theory Techn., vol. 64, no. 7, pp. 1997–2005, Jul. 2016.

[11] X. Guo, L. Zhu, and W. Wu, “A dual-wideband differential filter on strip-loaded slotline resonators with enhanced coupling scheme,” IEEE Microwave Compon. Lett., vol. 26, no. 11, pp. 882–884, Nov. 2016.

[12] F. Bagci, A. Fernandez-Prieto, A. Lujambio, J. Martel, J. Bernal, and F. Medina, “Compact balanced dual-band bandpass filter based on modified coupled-ended resonators,” IEEE Microwave Wireless Compon. Lett., vol. 27, no. 1, pp. 31–33, Jan. 2017.

[13] Z. J. Wang, C. Wang, and N. Y. Kim, “Dual-/triple-wideband microstrip bandpass filter using independent triple-mode stub-loaded resonator,” Microw. Opt. Technol. Lett., vol. 60, no. 1, pp. 56–64, 2018.

[14] S.-F. Zhang et al., “Design of dual-triband BPF with controllable bandwidth based on a quintuple-mode resonator,” Prog. Electromagn. Res. Lett., vol. 82, pp. 129–137, Feb. 2019, doi:10.2528/PIERL18111305.

[15] M. Zhang et al., “Design of wideband/dual-wideband/triband BPF based on a penta-mode resonator,” Prog. Electromagn. Res., vol. 72, pp. 135–143, Oct. 2018, doi:10.2528/PIER18050701.

[16] K.-H. Wang and J.-S. Li, “Compact tri-band BPF based on embedded asymmetric T-shape stub-loaded resonators,” in Proc. 12th Int. Symp. Antennas, Propag. EM Theory (ISAPE), Dec. 2018, pp. 1–3.

[17] M. Rahman and J.-D. Park, “A compact tri-band triband filter using two stub-loaded dual mode resonators,” Prog. Electromagn. Res. M, vol. 64, pp. 201–209, 2018.

[18] M.-M. Ma, Z.-X. Tang, X. Cao, and T. Qian, “Tri-band cross-coupling bandpass filter with rectangular defected ground structure array,” J. Electromagn. Waves Appl., vol. 32, no. 11, pp. 1409–1415, Jul. 2018.

[19] I. Jadidi, M. A. Honarvar, and F. Khajeh-Khalili, “Compact tri-band microstrip filter using three types of resonators for Bluetooth, WIMAX, and WLAN applications,” Prog. Electromagn. Res. C, vol. 91, pp. 241–252, May 2019, doi:10.2528/PIERC19012602.

[20] F. Song, B. Wei, L. Zhu, Y. Feng, R. Wang, and B. Cao, “A novel tri-band superconducting filter using embedded stub-loaded resonators,” IEEE Trans. Appl. Supercond., vol. 26, no. 8, pp. 1–9, Dec. 2016.

[21] S. Majidifar and M. Hayati, “New approach to design a compact triband microstrip filter using a multilayer structure,” TURKISH J. Electr. Eng. Comput. Sci., vol. 25, no. 5, pp. 4006–4012, 2017.

[22] C. Zhu, J. Xu, W. Kang, and W. Wu, “Synthesis design of microstrip triple-passband dual-bandstop filter based on λ/4 uniform-impedance resonators,” IEEE Microw. Wireless Compon. Lett., vol. 28, no. 3, pp. 209–211, Mar. 2018.

[23] Y.-C. Jiang, Y.-W. Chen, Y.-C. Lu, K.-J. Lin, T.-C. Tai, H.-W. Wu, and Y.-H. Wang, “New compact triple-passband bandpass filter with wide stopband,” in Proc. Int. Conf. Eng. Sci., Ind. Appl. (ICESIS), Aug. 2019, pp. 1–4.

[24] M.-H. Weng, C.-W. Hsu, Y. Lin, C.-Y. Tsai, and R.-Y. Yang, “A simple method to design a tri-bandpass filter using open-loop uniform impedance resonators,” J. Electromagn. Waves Appl., vol. 34, no. 1, pp. 103–115, Jan. 2020.

[25] M. AbdulRehman and S. Khalid, “Design of tri-band bandpass filter using symmetrical open stub loaded stepped impedance resonator,” Electron. Lett., vol. 54, no. 19, pp. 1126–1128, Sep. 2018.

[26] M. P. Mohan, A. Alphones, and M. F. Karim, “Triple band filter based on double periodic CRLH resonator,” IEEE Microwave Wireless Compon. Lett., vol. 28, no. 3, pp. 212–214, Mar. 2018.

[27] L. Liu, X. Liang, R. Jin, X. Bai, H. Fan, and J. Geng, “A compact and high-selectivity tri-band bandpass filter based on symmetrical stub-loaded square ring resonator,” Microw. Opt. Technol. Lett., vol. 62, no. 2, pp. 630–636, 2020.
[28] H.-W. Wu, L.-Y. Jian, Y.-W. Chen, and Y.-K. Su, “New triple-passband bandpass filter using multipath stub loaded resonators,” JEEE Microw. Wireless Compon. Lett., vol. 26, no. 3, pp. 186–188, Mar. 2016.

[29] D. Li, D. Wang, Y. Liu, X. Chen, and H. Wu, “Compact tri-band bandpass filter based on ring multi-mode resonator,” in IEEE MTT-S Int. Microw. Symp. Dig., May 2019, pp. 1–3.

[30] H. Liu, L. Zhang, J. Li, M. Luo, and L. Gao, “Design of novel compact tri-band bandpass filter using embedded resonators,” Electromagnetics, vol. 39, no. 3, pp. 137–146, Apr. 2019.

[31] S.-X. Zhang, L.-L. Qiu, and Q.-X. Chu, “Multiband balanced filters with controllable bandwidths based on slotline coupling feed,” JEEE Microw. Wireless Compon. Lett., vol. 27, no. 11, pp. 974–976, Nov. 2017.

[32] B. Ren, Z. Ma, H. Liu, X. Qian, P. Wen, C. Wang, and M. Ohira, “Balanced tri-band bandpass filter using sex-mode stepped-impedance square ring loaded resonators,” IEICE Electron. Express, vol. 15, no. 18, 2018, Art. no. 20180670.

[33] D. M. Pozar, Microwave Engineering. Hoboken, NJ, USA: Wiley, 2009.

[34] P. Wang, X. An, and Z.-Q. Lv, “A compact tri-band bandpass filter with independently controllable harmonic bandwidth by using two grounded vias,” Prog. Electromagn. Res. Lett., vol. 74, pp. 1–8, Apr. 2018, doi: 10.2528/PIERL17110209.

[35] M. U. Rahman, D. S. Ko, and J. D. Park, “A compact tri-band bandpass filter utilizing double mode resonator with 6 transmission zeros,” Microw. Opt. Technol. Lett., vol. 60, no. 7, pp. 1767–1771, 2018.

[36] A. Sami and M. Rahman, “A very compact quintuple band bandpass filter using multimode stub loaded resonator,” Prog. Electromagn. Res. C, vol. 93, pp. 211–222, Jul. 2019, doi: 10.2528/PIERC19040409.

[37] A. Basit and M. I. Khattak, “Designing modern compact microstrip planar quadband bandpass filter for hand held wireless applications,” Frequentz, vol. 1, Jan. 2020, doi: 10.1515/freq-2019-0159.

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[38] D. M. Pozar, Microwave Engineering. Hoboken, NJ, USA: Wiley, 2009.

[39] M. U. Rahman, D. S. Ko, and J. D. Park, “A compact tri-band bandpass filter utilizing double mode resonator with 6 transmission zeros,” Microw. Opt. Technol. Lett., vol. 60, no. 7, pp. 1767–1771, 2018.

[40] A. Sami and M. Rahman, “A very compact quintuple band bandpass filter using multimode stub loaded resonator,” Prog. Electromagn. Res. C, vol. 93, pp. 211–222, Jul. 2019, doi: 10.2528/PIERC19040409.

[41] A. Basit and M. I. Khattak, “Designing modern compact microstrip planar quadband bandpass filter for hand held wireless applications,” Frequentz, vol. 1, Jan. 2020, doi: 10.1515/freq-2019-0159.

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