Research Article

Multiwideband Bandpass Filter Based on Folded Quad Cross-Stub Stepped Impedance Resonator

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A multiwideband bandpass filter (MW-BPF) using a quad cross-stub stepped impedance resonator (QC-SSIR) was simulated, fabricated, and measured. The proposed QC-SSIR is designed on a four-series arrangement of crossed open stub (COS) structures where each open stub is developed with a step impedance resonator (SIR) structure to generate a wide bandwidth. Compared to the COS resonator, the QC-SSIR has a wider fractional bandwidth and good transmission coefficients and is compact. ABCD matrix analysis is used to investigate the filter structure. Furthermore, the MW-BPF is designed on an FR4 microstrip substrate with \( \varepsilon_r = 4.4\), thickness \( h = 1.6\) mm, and tan \( \delta = 0.0265\). The results show that the proposed MW-BPF using a QC-SSIR achieves transmission coefficients/fractional bandwidths of \(-0.60\) dB/49.3%, \(-1.49\) dB/18.7%, and \(-1.93\) dB/13.9% at 0.81 GHz, 1.71 GHz, and 2.58 GHz, respectively. Furthermore, to reduce the filter size, a folded QC-SSIR (FQC-SSIR) structure was also proposed. The results show that the proposed MW-BPF using an FQC-SSIR achieves transmission coefficients/fractional bandwidths of \(-0.57\) dB/49.6%, \(-1.21\) dB/17.7%, and \(-1.76\) dB/12.5% at 0.82 GHz, 1.80 GHz, and 2.62 GHz, respectively. The size of the proposed MW-BPF using an FQC-SSIR is reduced by up to 46% compared with the MW-BPF using a QC-SSIR. Finally, the performance of the simulated MW-BPF based on the QC-SSIR and FQC-SSIR was in good agreement with the measurement results.

1. Introduction

In recent years, a multiband transceiver has been required to improve efficiency and support the development of various types of wireless communication standards [1–3]. As a subsystem of a multiband transceiver, a multiband bandpass filter (MB-BPF) is an important and essential component to reduce noise and interference at several frequency bands simultaneously [4, 5]. Microstrip filters play a significant role in the multiband microwave filter design because of their advantages in terms of fabrication simplicity, miniaturization, low loss, and low cost [6, 7]. Some attractive methods frequently used for the MB-BPF design include quarter-wave-length step impedance resonators (SIRs) [8], trisection SIRs [9–12], cascaded multiband resonators [13], loaded crossed resonators [14], stub-loaded resonators (SLRs) [15], trimode SLRs [16], stub-loaded quarter-wavelength resonators [17], stub-loaded and defected ground resonators (DGSs) [18, 19], and crossed open stubs (COSs) [20–22]. The most challenging part of an MB-BPF design is to allow several passbands simultaneously without sacrificing any design freedom or additional drawbacks such as complex geometry and
increasing size. Recently, some studies of an MB-BPF have been published in [8–22]. The results show a good electrical performance; however, the additional passbands would make the size of the BPF greater and the bandwidth narrower. Several studies on miniaturized microstrip BPFs have been reported such as BPFs using microstrip E-shaped bandpass filters [23], coupled slotted open stubs [24], and meander coupled lines [25].

The performance of an MB-BPF using a COS is proposed and evaluated in [21, 22], but these studies only resulted in a BPF with a narrow bandwidth. A COS method is an expansion method of SLRs, which is implemented by two open stubs with crossed positions; it is a good method due to its direct coupling. Therefore, the COS method has a good transmission coefficient ($S_{21}$) [21]. Moreover, the transmission zeros (TZs) can be easily controlled by adjusting the lengths and impedances of the COS.

Some research on multiband BPF (MW-BPF) was proposed in [24–26]. A very compact quarter band BPF utilizing a multimode stub-loaded resonator (MSLR) was proposed in [26]. The proposed filter utilizes two coupled stub-loaded dual-mode resonators (SLDMRs) instead of three sets of resonators to achieve a compact triband BPF with good transmission coefficient and high selectivity [27]. A dual-wideband BPF and a triwideband BPF for 5G mobile communications are proposed in [28]. The dual-wideband BPF is achieved by two folded open-loop stepped impedance resonators (FOLSRs), and then, by placing a pair of folded uniform impedance resonators (FUIRs) inside the dual-wideband BPF, a triwideband BPF is constituted with little influence on the physical size of the filter. The structure of the MW-BPF is complicated. A multiband BPF using a folded SIR was proposed in [4, 14, 29]; however, it generates a narrow bandwidth.

As novelty, compact multiband BPFs with a wide bandwidth and good transmission coefficient, a quad cross-stub stepped impedance resonator (QC-SSIR) was proposed. The QC-SSIRs are expanded COS structures. Typically, the COS structures are arranged serially depending on the number of bands to be produced, as shown in Figure 1(a). However, the bandwidth is still narrow. The combination of several COSs with the SIR structure called a crossed stub-SIR (CS-SIR) will be used to produce a wider bandwidth than the COS structure. This paper will propose three wideband BPFs using 4 CS-SIRs called quad-CS-SIRs (QC-SSIRs), as shown in Figure 1(b). Furthermore, to reduce the filter size, a folded QC-SSIR (FQC-SSIR) structure was proposed, as shown in Figure 1(c). As a result, the proposed multiband BPF exhibits not only a wide bandwidth, as shown in Figure 1(d), but also a compact size.

Furthermore, MW-BPFs using a QC-SSIR and FQC-SSIR were designed on an FR4 microstrip substrate with $\varepsilon_r = 4.4$, thickness $h = 1.6$ mm, and loss tangent $\delta = 0.0265$. The MW-BPF is simulated by using the momentum simulation advanced system design (ADS). To validate the proposed method, the multiband BPF has been tested. The structure of this paper is as follows. Section 1 gives an overview of the proposed multiband BPF. Section 2 analyzes the structure of the COS, QC-SSIR, and FQC-SSIR. Section 3 focuses on the fabrication and measurement. Finally, Section 4 concludes this research.

2. Proposed COS, QC-SSIR, and FQC-SSIR Structure

This section analyzes the structure of a COS resonator, QC-SSIR, and FQC-SSIR based on ABCD matrix investigation.

2.1. Crossed Open Stub (COS) Structure. The COS resonator structure and the ABCD matrix structure for COS are shown in Figures 2(a) and 2(b), respectively. The input/output port is connected to 50 $\Omega$. In the COS topology, $W_N$ and $Z_N$ (for $N = S, 0, 1A, 2A, 3A$) represent the width and impedance of the resonator, respectively. $L_N$ and $\theta_N$ (for $N = S, 0, 1A, 2A, 3A$) represent the physical length and electric length of the resonator, respectively. Furthermore, $M_N$ (for $N = 1A, 2A, 3A$, COS) represents the ABCD matrix structure.

The ABCD matrix of the COS with the impedance of the transmission line, $Z_N$, and electrical length, $\theta_N$, can be obtained as [20–22]

$$\left[ \begin{array}{cc} A & B \\ C & D \end{array} \right] = M_{1A} M_{\cos(A)} M_{1A}, \quad (1)$$

with $M_{1A}$ [30] as

$$M_{1A} = \left[ \begin{array}{ccc} \cos \theta_{1A} & jZ_{1A} \sin \theta_{1A} \\ j \sin \theta_{1A} & \cos \theta_{1A} \end{array} \right], \quad (2)$$

and $M_{\cos(A)}$ can be calculated by parallel operation between $Z_{2A}$ and $Z_{3A}$:

$$Z_{\cos(A)} = \frac{Z_{2A} Z_{3A} \cot \theta_{2A} \cos \theta_{3A}}{j(Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A})}. \quad (3)$$

Because $M_{\cos(A)}$ has a position as open-stub circuited, the ABCD matrix of $M_{\cos(A)}$ becomes [31]

$$M_{\cos(A)} = \left[ \begin{array}{cc} 1 & 0 \\ Y_{\cos(A)} & 1 \end{array} \right] = \left[ \begin{array}{cc} 1 & 0 \\ \frac{j(Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A})}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} & 1 \end{array} \right]. \quad (4)$$

Furthermore, the element matrix from equation (1) can determined as follows:

$$\begin{align*}
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} &= M_{1A} M_{\cos(A)} M_{1A}, \\
M_{1A} &= \begin{bmatrix}
\cos \theta_{1A} & jZ_{1A} \sin \theta_{1A} \\
\cos \theta_{1A} & \sin \theta_{1A}
\end{bmatrix}, \\
M_{\cos(A)} &= \begin{bmatrix}
1 & 0 \\
Y_{\cos(A)} & 1
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
\frac{j(Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A})}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} & 1
\end{bmatrix}.
\end{align*}$$

Furthermore, the element matrix from equation (1) can determined as follows:
COS resonator:
1. Multiband
2. Narrow passband
3. Large size

QC-SSIR resonator:
1. Multiband
2. Wide passband
3. Large size

Folded QC-SSIR resonator:
1. Multiband
2. Wide passband
3. Small size

Figure 1: The resonator structure: (a) crossed open stub resonator, (b) quad cross-stub stepped impedance resonator (proposed), (c) folded quad cross-stub stepped impedance resonator (proposed), and (d) comparison of bandwidth of the COS and QC-SSIR structure.

Figure 2: (a) The COS resonator structure and (b) the ABCD matrix structure for the COS resonator.
\begin{align*}
A_A &= \cos^2 \theta_A - \frac{Z_{1A} \sin \theta_{1A} \cos \theta_{1A} (Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A})}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} - \sin^2 \theta_{1A}, \\
B_A &= jZ_{1A} \sin \theta_{1A} \left( \cos \theta_{1A} - \frac{Z_{1A} \sin \theta_{1A} (Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A})}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} \right) + jZ_{1A} \sin \theta_{1A} \cos \theta_{1A}, \\
C_A &= \frac{j \sin \theta_{1A} \cos \theta_{1A}}{Z_{1A}} - \frac{\sin \theta_{1A} \cos \theta_{1A}}{Z_{1A}} \left( \frac{Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A}}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} \right), \\
D_A &= -\sin^2 \theta_{1A} + j \cos^2 \theta_{1A} \left( \frac{Z_{2A} \cot \theta_{2A} + Z_{3A} \cot \theta_{3A}}{Z_{2A} Z_{3A} \cot \theta_{2A} \cot \theta_{3A}} \right).
\end{align*}

(5)

To simplify the derivatives, we can set \( \theta \) to \( \lambda/4 \) line or \( 90' \) so that the responses are determined by impedance only. Furthermore, to make equation (1) the closed-form equations, the same approach as proposed in [20–22] was used, which is that the ABCD matrix of the system is equivalent to the \( \lambda/4 \) line or set to the matching condition. Thus, the matrix ABCD can be written as

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} =
\begin{bmatrix}
\cos \vartheta & jZ_0 \sin \vartheta \\
-jZ_0 \sin \vartheta & \cos \vartheta
\end{bmatrix}
\begin{bmatrix}
0 & jY_0 \\
-jY_0 & 0
\end{bmatrix}.
\]

(6)

By solving equations (1) and (6), the transmission line impedance \( (Z_N) \) and electrical length \( (\theta_N) \) of the COS resonator can be found. Finally, the relation of the ABCD matrix and the scattering parameters of \( S_{11} \) and \( S_{21} \) is determined by equations (7) and (8) [30], respectively:

\[
S_{11} = \frac{A + B Y_0 - C Z_0 - D}{A + B Y_0 + C Z_0 + D},
\]

(7)

\[
S_{21} = \frac{2}{A + B Y_0 + C Z_0 + D}.
\]

(8)

This conventional COS method only resulted in a narrow bandwidth and generated more than 3 resonance frequencies. To extend the bandwidth and reduce the number of resonance frequencies, this paper proposed a QC-SSIR to generate the MW-BPF. The proposed QC-SSIR is constructed by employing 2 identical SSIRs placed side by side, as shown in Figure 3(a).

2.2. Quad Cross-Stub Stepped Impedance Resonator (QC-SSIR) Structure. The proposed QC-SSIR structure and the ABCD matrix structure for the QC-SSIR are shown in Figures 3(a) and 3(b), respectively. The input/output port is connected to \( 50 \Omega \). In the QC-SSIR topology, \( W_N \) and \( Z_N \) (for \( N = S, 0, 1B, 2B, 3B, 4B, 5B \)) represent the width and impedance of the resonator, respectively. \( L_N \) and \( \theta_N \) (for \( N = S, 0, 1B, 2B, 3B, 4B, 5B \)) represent the physical length and electrical length of the resonator, respectively. Furthermore, \( M_N \) (for \( N = 1B, 2B, 3B, 4B, 5B, \) COS) represents the ABCD matrix structure.

The ABCD matrix of the QC-SSIR structure can be determined as follows:

\[
\begin{bmatrix}
A_B & B_B \\
C_B & D_B
\end{bmatrix} = M_{1B} M_{2B} M_{3B} M_{4B} M_{5B} M_{6B} M_{7B} M_{8B} M_{1B},
\]

(9)

with

\[
M_{1B} = \begin{bmatrix}
\cos \theta_{1B} & jZ_{1B} \sin \theta_{1B} \\
-jZ_{1B} \sin \theta_{1B} & \cos \theta_{1B}
\end{bmatrix},
\]

(10)

\[
M_{5B} = \begin{bmatrix}
\cos \theta_{5B} & jZ_{5B} \sin \theta_{5B} \\
-jZ_{5B} \sin \theta_{5B} & \cos \theta_{5B}
\end{bmatrix},
\]

and \( M_{\cos(B)} \) can be calculated by parallel operation between \( Z_{2B} \) and \( Z_{\text{SIR}(B)} \):

\[
Z_{\text{SIR}(B)} = \frac{j (Z_{4B} \cot \theta_{4B} + Z_{4B} \tan \theta_{4B})}{Z_{3B} (Z_{4B} - Z_{3B} \tan \theta_{4B} \cot \theta_{4B})},
\]

\[
Z_{\cos(B)} = \frac{Z_{2B} Z_{3B} \cot \theta_{2B} \tan \theta_{4B} + Z_{2B} Z_{4B} \cot \theta_{2B} \tan \theta_{4B} - jZ_{2B} \cot \theta_{2B}}{Z_{2B} Z_{3B} \cot \theta_{2B} \tan \theta_{4B} + Z_{2B} Z_{4B} \cot \theta_{2B} \tan \theta_{4B}}.
\]

(11)

Because \( M_{\cos(B)} \) has a position as open-stub circuited, the ABCD matrix of \( M_{\cos(B)} \) becomes

\[
M_{\cos(B)} = \begin{bmatrix}
1 & 0 \\
Y_{\cos(B)} & 1
\end{bmatrix} = \begin{bmatrix}
\frac{Z_{1B} Z_{4B} - Z_{3B}^2}{Z_{2B} Z_{3B} \cot \theta_{2B} \tan \theta_{4B} + Z_{2B} Z_{4B} \cot \theta_{2B} \tan \theta_{4B}} & 0 \\
0 & 1
\end{bmatrix},
\]

(12)
To simplify the derivatives, we can set $\theta$ to $\lambda/4$ line or 90° so that the responses are determined by impedance only. The scattering parameters of $S_{11}$ and $S_{21}$ of the QC-SSIR structure can be obtained by solving equations (6)–(9).

Furthermore, Figures 4(a) and 4(b) show the transmission coefficients ($S_{21}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF with a QC-SSIR with varied $L_{2B}$ values. The $L_{2B}$ is varied from 0.5 mm to 4.5 mm by using ADS full-wave simulation software. The figure shows that the transmission coefficients at center frequencies of $f_1, f_2$, and $f_3$ are stable; it also shows that the $L_{2B}$ changes only slightly affect $f_2$ and $f_3$. Moreover, the variation in $L_{2B}$ was affected by the reflection coefficients ($S_{11}$) of $f_2$ and $f_3$. Furthermore, the decrease in the reflection coefficient ($S_{11}$) of $f_3$ at $L_{2B} = 4.5$ mm is still lower than −10 dB.

Moreover, Figures 5(a) and 5(b) illustrate the transmission coefficients ($S_{21}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF using a QC-SSIR with varied $L_{5B}$ values. The $L_{5B}$ is varied from 3 mm to 15 mm. Figure 5(a) also shows the transmission zero frequencies, which were located at 1.2 GHz, 2.16 GHz, and 3.07 GHz. The result shows that the MW-BPF has three transmission zeros with good isolation. Figure 5(b) shows that the variation in $L_{5B}$ was affected by the reflection coefficient ($S_{11}$) values, yet it has a slight effect on the frequency shift.

Figures 6(a)–6(c) show the reflection coefficients, transmission coefficients, and resonant frequencies of the MW-BPF using a QC-SSIR with varied $W_{4B}/W_{3B}$ values.

It can be seen from Figure 6(a) that the reflection coefficients ($S_{11}$) of frequencies $f_1, f_2,$ and $f_3$ can be tuned by modifying the values of $W_{4B}/W_{3B}$, whereas the reflection coefficients ($S_{11}$) of frequencies $f_1, f_2,$ and $f_3$ vary slightly. Meanwhile, Figure 6(b) shows the extracted transmission coefficients ($S_{21}$) with varied $W_{4B}/W_{3B}$ values. It can be seen that the transmission coefficients ($S_{21}$) of frequencies $f_1, f_2,$ and $f_3$ are always increasing. Moreover, Figure 6(c) shows the resonant frequencies, where the frequency centers $f_1, f_2,$ and $f_3$ vary slightly. In general, the variation in $W_{4B}/W_{3B}$ only affects the transmission coefficient values but does not affect the frequency shift. Furthermore, to reduce the filter size, a folded QC-SSIR (FQC-SSIR) structure was also proposed, as shown in Figure 7(a).

2.3. Folded Quad Cross-Stub Stepped Impedance Resonator (FQC-SSIR) Structure. The proposed folded quad cross-stub stepped impedance resonator (FQC-SSIR) structure and the ABCD matrix structure for the FQC-SSIR are shown in Figures 7(a) and 7(b), respectively. The input/output port is connected to 50 Ω. In the FQC-SSIR topology, $W_N$ and $Z_N$ (for $N = S, 0, 1C, 2C, 3C, 4C, 5C$) represent the width and impedance of the resonator, respectively. $L_N$ and $\theta_N$ (for $N = S, 0, 1C, 2C, 3C, 4C, 5C$) represent the physical length and electric length of the resonator, respectively.
Furthermore, $M_N$ (for $N = 1C, 2C, 3C, 4C, 5C, \text{COS}$) represents the ABCD matrix structure.

The ABCD matrix of the folded QC-SSIR structure can be determined as follows:

$$
\begin{bmatrix}
A_C & B_C \\
C_C & D_C
\end{bmatrix} = 
\begin{bmatrix}
M_{1C} & M_{1C}M_{2C}M_{3C}M_{4C}M_{5C}M_{6C}M_{7C}M_{8C}M_{9C}M_{10C}M_{11C}M_{12C}M_{13C}M_{14C}M_{15C}
\end{bmatrix},$$

(13)

with

$$
M_{1C} = \begin{bmatrix}
\cos \theta_{1C} & j Z_{1C} \sin \theta_{1C} \\
j \sin \theta_{1C} & \cos \theta_{1C}
\end{bmatrix},
$$

and

$$
M_{2C} = \begin{bmatrix}
\cos \theta_{2C} & j Z_{2C} \sin \theta_{2C} \\
j \sin \theta_{2C} & \cos \theta_{2C}
\end{bmatrix},
$$

(14)

Figure 4: (a) The transmission coefficients ($S_{21}$) of the proposed MW-BPF using a QC-SSIR with varied $L_{2B}$ values. (b) The reflection coefficients ($S_{11}$) of the proposed MW-BPF using a QC-SSIR with varied $L_{2B}$ values.

Figure 5: (a) The transmission coefficients ($S_{21}$) of the proposed MW-BPF using a QC-SSIR with varied $L_{5B}$ values. (b) The reflection coefficients ($S_{11}$) of the proposed MW-BPF using a QC-SSIR with varied $L_{5B}$ values.

Furthermore, $M_N$ (for $N = 1C, 2C, 3C, 4C, 5C, \text{COS}$) represents the ABCD matrix structure.
Figure 6: (a) The extracted reflection coefficients, (b) extracted transmission coefficients, and (c) extracted resonant frequencies of an MW-BPF using a QC-SSIR with varied $W_{4B}/W_{3B}$ values.

Figure 7: (a) FQC-SSIR structure and (b) the ABCD matrix structure for the FQC-SSIR.
and $M_{\cos(C)}$ can be calculated by parallel operation between $Z_{2C}$ and $Z_{SIRC}$:

$$Z_{SIRC} = \frac{j(Z_{SC} \tan \theta_{AC} + Z_{4C} \tan \theta_{AC})}{Z_{SC}(Z_{4C} - Z_{SC} \tan \theta_{AC} \tan \theta_{AC})},$$

$$Z_{\cos(C)} = \frac{Z_{2C}Z_{4C} \cot \theta_{AC} \tan \theta_{AC} + Z_{2C}Z_{4C} \cot \theta_{AC} \tan \theta_{AC} - jZ_{2C} \cot \theta_{AC}}{Z_{SC}Z_{4C} \cot \theta_{AC} \tan \theta_{AC} - jZ_{2C} \cot \theta_{AC}}.$$

(15)

To simplify the derivatives, we can set $\theta$ to $\lambda/4$ line or 90° so that the responses are determined by impedance only. The scattering parameters of $S_{11}$ and $S_{21}$ can be obtained by solving equations (6)–(8) and (13).

Furthermore, Figures 8(a) and 8(b) show the transmission coefficients ($S_{11}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF with a QC-SSIR with varied $L_{2C}$ values. The $L_{2C}$ is varied from 1.5 mm to 13.5 mm.

Figure 8(a) shows that the transmission coefficients at the center frequency of $f_1$ are stable. It also shows that the $L_{2C}$ changes affect $f_2$ and $f_3$. The 3rd bandwidth is degraded for the value $L_{2C}$ = 13.5 mm. Furthermore, Figure 8(b) shows that the variation in $L_{2B}$ was highly affected by the reflection coefficients ($S_{12}$) of $f_2$ and $f_3$. It can be observed that by increasing the length of $L_{2C}$, the center frequencies of $f_2$ and $f_3$ gradually decrease. The reflection coefficient value ($S_{11}$) of $f_3$ is significantly decreased at $L_{2B}$ = 13 mm. However, the values are still lower than −10 dB, with a relatively narrow bandwidth.

Furthermore, Figures 9(a) and 9(b) show the transmission coefficients ($S_{11}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF using an FQC-SSIR with varied $L_{2C}$ values, respectively. It is clear from Figure 9(a) that the value of $S_{21}$ is stable for $f_1$, $f_2$, and $f_3$. The graph indicates that the 4th passband does not appear because the value of $S_{21}$ is lower than −3 dB. Moreover, the values of $S_{11}$ for $f_1$, $f_2$, and $f_3$ are significantly changed by varying $L_{2C}$. Figures 10(a)–10(c) show the reflection coefficients, transmission coefficients, and resonant frequencies of the MW-BPF using an FQC-SSIR with varied $W_{3C}$/$W_{SC}$ values.

Figure 10(a) shows that the reflection coefficients ($S_{11}$) of frequency $f_1$ can be tuned by modified values of $W_{4B}$/$W_{3B}$, whereas the reflection coefficients ($S_{11}$) of frequencies $f_2$ and $f_3$ vary slightly. Additionally, Figure 10(b) shows the extracted transmission coefficients ($S_{12}$) with varied $W_{4B}$/$W_{3B}$ values, and it can be seen that the transmission coefficients ($S_{12}$) of frequencies $f_1$, $f_2$, and $f_3$ moderately increase. Moreover, Figure 10(c) shows the extracted resonant frequencies, where the frequency centers $f_1$, $f_2$, and $f_3$ are mostly stable. In general, the variation in $W_{4C}$/$W_{SC}$ only affects the reflection coefficient and marginally affects the transmission coefficient values or the frequency shift.

Furthermore, Figure 11 shows the transmission coefficients ($S_{11}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF using a folded QC-SSIR with a varied bend/corner structure. The performance of $S_{21}$ and $S_{11}$ by using the curve bend, square bend, and chamfer bend is compared. It is clearly seen that the chamfer bend generated good performance. However, the center frequencies of $f_1$, $f_2$, and $f_3$ are moderately shifted.

3. Implementation of an MW-BPF Using a QC-SSIR and FQC-SSIR

To validate the proposed method, this section focuses on the fabrication and measurement. Figures 3(a) and 7(a) show the final schematic of the designed MW-BPF using a QC-SSIR and FQC-SSIR, respectively. The optimum dimensions of the MW-BPF structure using a QC-SSIR and FQC-SSIR were simulated by ADS. Furthermore, the proposed MW-BPF was fabricated on a microstrip with $\varepsilon_r = 4.4$, $h = 1.6$ mm, and $\tan \delta = 0.0265$. As shown in Figure 3(a), the lengths of the transmission lines are $W_0 = 3.5$ mm, $W_{1B} = 1.0$ mm, $W_{2B} = 1.5$ mm, $W_{3B} = 2.5$ mm, $W_{4B} = 7.5$ mm, $W_{5B} = 2.5$ mm, $L_0 = 25$ mm, $L_{1B} = 1.0$ mm, $L_{2B} = 1.5$ mm, $L_{3B} = 77$ mm, $L_{4B} = 20$ mm, and $L_{5B} = 9.0$ mm. An FQC-SSIR structure is proposed to reduce the MW-BPF size, as shown in Figure 7(a). This miniaturization is performed by folding/rotating the length transmission line of the $L_{3B}$ total length set to a constant of 77 mm. Moreover, the lengths of the transmission lines are $W_0 = 3.5$ mm, $W_{1C} = 1.0$ mm, $W_{2C} = 1.5$ mm, $W_{3C} = 2.5$ mm, $W_{4C} = 7.5$ mm, $W_{5C} = 2.5$ mm, $L_0 = 25$ mm, $L_{1C} = 1.0$ mm, $L_{2C} = 1.5$ mm, $L_{3C} = 36$ mm, $L_{4C} = 25$ mm, $L_{5C} = 36$ mm, $L_{5C} = 11$ mm, $L_{5C} = 5.0$ mm, $L_{4C} = 20$ mm, and $L_{5C} = 9.0$ mm.

Figures 12(a) and 12(b) show photographs of the MW-BPF using a QC-SSIR and FQC-SSIR, respectively. Figure 12(a) shows that the MW-BPF using a QC-SSIR has a size of $97$ mm $\times$ $240$ mm ($W_B \times L_B$). Meanwhile, the MW-BPF using an FQC-SSIR has a size of $97$ mm $\times$ $129$ mm.
\((W_c \times L_B)\), as shown in Figure 12(b). Therefore, the size of the proposed MW-BPF with an FQC-SSIR is reduced by 46% compared to that of the MW-BPF with a QC-SSIR.

Figures 13(a) and 13(b) show comparisons between the simulated and measured results of the MW-BPFs using a QC-SSIR and FQC-SSIR in terms of the transmission coefficients \((S_{21})\) and reflection coefficients \((S_{11})\). We can see from Figure 13(a) that the value of transmission coefficients \((S_{21})\) has a ripple around a frequency of 1.8 GHz. However, this ripple does not occur at other frequencies, such as at the first band and the third band. We have investigated the cause of this ripple, and the results show that imperfections in the cables and connectors cause the ripple. Overall, the performance of the proposed MW-BPF using an FQC-SSIR is slightly shifted within acceptable limits compared with the MW-BPF using a QC-SSIR. Both the MW-BPF using a QC-SSIR and that using an FQC-SSIR obtained good reflection coefficients lower than \(-10\) dB.

The MW-BPF using a QC-SSIR achieves transmission coefficients/fractional bandwidths of 0.60 dB/49.3\%, 1.49 dB/18.7\%, and 1.93 dB/13.9\% at 0.81 GHz, 1.71 GHz, and 2.58 GHz, respectively. Moreover, the MW-BPF using an FQC-SSIR achieves transmission coefficients/fractional bandwidths of 0.57 dB/50.6\%, 1.47 dB/19.1\%, and 1.92 dB/13.5\% at 0.81 GHz, 1.71 GHz, and 2.58 GHz, respectively.
Figure 10: (a) The reflection coefficients, (b) transmission coefficients, and (c) resonant frequencies of the MW-BPF using an FQC-SSIR with varied $W_{4C}/W_{3C}$ values.

Figure 11: The transmission coefficients ($S_{21}$) and reflection coefficients ($S_{11}$) of the proposed MW-BPF using an FQC-SSIR with a varied bend/corner structure.
Figure 12: Photograph of MW-BPFs using a (a) QC-SSIR and (b) FQC-SSIR.

Figure 13: Comparison between the simulated and measured results of the MW-BPF using a QC-SSIR and FQC-SSIR in terms of the (a) transmission coefficients ($S_{21}$) and (b) reflection coefficients ($S_{11}$).
Figure 14: Surface current flow of a QC-SSIR at (a) $f_1$, (b) $f_2$, and (c) $f_3$ and an FQC-SSIR at (d) $f_1$, (e) $f_2$, and (f) $f_3$.

Table 1: Summary of the proposed multiwideband BPF comparison.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Year</th>
<th>Method</th>
<th>Center frequency (GHz)</th>
<th>Transmission coefficients (dB)</th>
<th>$-3$ dB FBW (%)</th>
<th>Size ($\lambda_g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[8]</td>
<td>2006</td>
<td>Quarter-wavelength SIRs</td>
<td>1.57/2.45/5.25</td>
<td>$-1.50/-1.34/-0.90$</td>
<td>8.2/7.3/9.9</td>
<td>0.06 × 0.09</td>
</tr>
<tr>
<td>[10]</td>
<td>2007</td>
<td>Trisection SIRs</td>
<td>1.57/2.45/3.50</td>
<td>$-1.95/-2.42/-2.00$</td>
<td>7.0/4.2/9.0</td>
<td>0.12 × 0.09</td>
</tr>
<tr>
<td>[13]</td>
<td>2006</td>
<td>Cascaded multiband resonators</td>
<td>2.30/3.70/5.50</td>
<td>$-2.50/-1.90/-2.90$</td>
<td>3.8/6.8/5.0</td>
<td>0.28 × 0.08</td>
</tr>
<tr>
<td>[14]</td>
<td>2009</td>
<td>Loaded crossed resonator</td>
<td>2.40/3.50/5.20</td>
<td>$-1.40/-1.50/-1.80$</td>
<td>3.0/3.0/3.0</td>
<td>0.18 × 0.20</td>
</tr>
<tr>
<td>[16]</td>
<td>2010</td>
<td>Trimode stub-loaded resonators (SLRs)</td>
<td>2.45/3.56/5.90</td>
<td>$-0.80/-1.60/-1.80$</td>
<td>7.59/5.86/3.71</td>
<td>0.16 × 0.20</td>
</tr>
<tr>
<td>[17]</td>
<td>2011</td>
<td>Stub-loaded quarter-wavelength resonator</td>
<td>1.80/2.40/3.00</td>
<td>$-0.30/-0.30/-0.20$</td>
<td>9.4/12.5/6.4</td>
<td>0.23 × 0.30</td>
</tr>
<tr>
<td>[19]</td>
<td>2010</td>
<td>Stub-loaded and DGS resonator</td>
<td>2.45/3.50/5.25</td>
<td>$-0.90/-1.70/-2.10$</td>
<td>12.3/6.2/3.3</td>
<td>0.26 × 0.32</td>
</tr>
<tr>
<td>[22]</td>
<td>2010</td>
<td>Crossed open stubs</td>
<td>2.45/3.50/5.22</td>
<td>$-0.80/-0.80/-0.80$</td>
<td>15.1/13.4/7.6</td>
<td>0.20 × 0.30</td>
</tr>
<tr>
<td>[27]</td>
<td>2018</td>
<td>Two stub-loaded dual-mode resonators</td>
<td>1.57/2.40/3.45</td>
<td>$-0.70/-1.14/-0.3$</td>
<td>28.6/7.5/5.21</td>
<td>0.44 × 0.56</td>
</tr>
<tr>
<td>[28]</td>
<td>2020</td>
<td>Folded open-loop stepped impedance resonators</td>
<td>2.17/3.51/4.86</td>
<td>$-0.46/-0.49/-1.30$</td>
<td>12.4/11.4/13.3</td>
<td>0.22 × 0.22</td>
</tr>
<tr>
<td>[32]</td>
<td>2019</td>
<td>Common resonator feeding</td>
<td>3.0/6.0/9.0</td>
<td>$-3.06/-2.71/-3.16$</td>
<td>3.06/2.71/3.16</td>
<td>0.15 × 0.12</td>
</tr>
<tr>
<td>[33]</td>
<td>2019</td>
<td>Asymmetric shunted-line stepped impedance resonator</td>
<td>1.57/2.40/3.50</td>
<td>$-0.10/-0.09/-0.11$</td>
<td>5.2/4.25/2.7</td>
<td>0.076 × 0.26</td>
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<tr>
<td>[34]</td>
<td>2020</td>
<td>Multicoupled line stub-SIR</td>
<td>1.75/2.55/3.55</td>
<td>$-0.55/-1.37/-1.37$</td>
<td>21.2/4.7/8.4</td>
<td>0.32 × 0.12</td>
</tr>
</tbody>
</table>

This work

Table 1(a) Quad cross-stub stepped impedance resonator (QC-SSIR) 0.81/1.71/2.58 $-0.60/-1.49/-1.93$ 49.3/18.7/13.9 0.27 × 0.66

Table 1(b) Folded quad cross-stub stepped impedance resonator (FQC-SSIR) 0.82/1.80/2.62 $-0.57/-1.21/-1.76$ 49.6/17.7/12.5 0.27 × 0.35

$\lambda_g$ is the guided wavelength on the substrate at the center frequency of the first passband.
bandwidths of 0.57 dB/49.6%, 1.21 dB/17.7%, and 1.76 dB/12.5% at 0.82 GHz, 1.80 GHz, and 2.62 GHz, respectively. Furthermore, Figures 14(a)–14(f) show the surface current flow of a QC-SSIR at $f_1$, $f_2$, and $f_3$ and a folded QC-SSIR at $f_1$, $f_2$, and $f_3$. Different surface current flows are clearly observed at different frequencies. Moreover, Table 1 summarizes the comparison of the various proposed BPFs. Furthermore, this result indicated that the QC-SSIR can be utilized to produce a multiband BPF for multiband applications. Good agreement can be observed between the simulated and measured results, which demonstrates the validity of the design.

4. Conclusion

The MW-BPF was successfully designed and implemented using a QC-SSIR microstrip structure. The MW-BPF using a QC-SSIR achieves transmission coefficients/fractional bandwidths of 0.60 dB/49.3%, 1.49 dB/18.7%, and 1.93 dB/13.9% at 0.81 GHz, 1.71 GHz, and 2.58 GHz, respectively. The QC-SSIR has a size of 97 mm $\times$ 240 mm ($W_B \times L_B$). To reduce the filter size, an FQC-SSIR was proposed. The MW-BPF using a FQC-SSIR achieves transmission coefficients/fractional bandwidths of 0.57 dB/49.6%, 1.21 dB/17.7%, and 1.76 dB/12.5% at 0.82 GHz, 1.80 GHz, and 2.62 GHz, respectively. The QC-SSIR has a size of 97 mm $\times$ 129 mm ($W_c \times L_c$). Therefore, the size of the proposed MW-BPF with an FQC-SSIR is reduced by 46% compared with that of the MW-BPF with a QC-SSIR. In comparison with previous works, the QC-SSIR microstrip structure could produce wide bandwidth and good transmission coefficients. The simulated and measured results are in good agreement.

Data Availability

The datasets are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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