Design of Microstrip Multifunction Integrated Diplexers With Frequency Division, Frequency Selection, and Power Division Functions

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ABSTRACT In this study, a novel circuit model was proposed for the design of multifunction integrated diplexers with frequency division, frequency selection, and power division functions. The proposed highly integrated multifunctional diplexer mainly comprises only two different-frequency multimode resonators and two isolation resistors, which results in a compact circuit size. The distributed coupling technique was adopted to integrate the two multimode resonators. One resonator was used to form a channel passband, and the other resonator was used to form another channel passband. Moreover, each channel passband can be independently designed and flexibly allocated. The two resistors loaded between the output feeding lines were introduced to improve the impedance matching of the output ports and the isolation between the output ports for each channel. The coupling structures, theoretical analysis, and design procedure for the proposed multifunction integrated diplexers are described. For demonstration, multifunction integrated diplexers with second-order and third-order filtering responses were designed and fabricated using microstrip technology. The experiment and simulation results were consistent and indicated satisfactory in-band and out-of-band performance.

INDEX TERMS Bandpass filter (BPF), diplexer, microstrip, multifunction, power divider (PD).

I. INTRODUCTION
In latest RF and microwave multiband wireless communication systems, multifunctional devices play a crucial role. To improve system integration, reducing the system size and economic cost and developing multifunctional devices are urgently needed. Integrating a bandpass filter (BPF) and power divider (PD) into a single device, namely a filtering PD, is a popular research subject [1]–[27].

The filtering PDs in [1]–[6] have been designed based on the coupled resonator technology, in which the coupling between resonators is a substitute for the quarter-wavelength (λ/4) line of a traditional Wilkinson PD, which provides the PD with a frequency selection function. The filtering PDs in [7]–[13] have been designed for dual-band applications. Dual-band filtering PDs integrated with dual-mode stub-loaded resonators have been developed in [7], [8]. In [9], four dual-mode resonators were used and symmetrically placed along the input feeding line to obtain the dual-band filtering response and power division. The filtering PD in [10] was based on a traditional Wilkinson PD. Here, the λ/4 line of the Wilkinson PD was replaced by a T-junction structure for dual-band power division. Moreover, three λ/4 stepped-impedance resonators were added to the three ports of the PD for frequency selection. In [11], the generalized dual-band BPFs with arbitrary bandwidth and arbitrary source and loaded impedances replaced the λ/4 lines in the traditional PD. In [12], a filtering PD consisting of a resonator loaded λ/4 three-line coupled structure and a modified isolation network including two isolation resistors was proposed. In [13], a single quad-mode resonator was adopted to construct a filtering PD to simultaneously achieve the dual-band filtering response and power division. The filtering PDs in [14]–[16] have been designed for wideband...
applications. In [14], a terminated coupled-line structure was used to realize a wideband filtering PD with balanced out-of-band performance. In [15], a wideband filtering PD utilizing the coupled-line sections and the open- or short-circuited stubs was investigated. In [16], a pair of tri-mode resonators was used to design a filtering PD. A wideband response was achieved by properly controlling the coupling strengths. In [17], from the distinctive voltage distribution along an open-ended one-wavelength transmission line, two identical dual-mode resonators and the open-ended transmission line were used to construct the filtering PD. In [18], a filtering PD was initially constructed using a single dual-mode resonator and an isolation resistor. Moreover, three open-ended stubs loaded at the input and outputs were introduced to improve the out-of-band response. Furthermore, the filtering PDs in [19]–[23] have a tunable center frequency. In [24], a filtering PD with favorable port-to-port isolation performance was proposed. Because the conventional isolation network was replaced by a distributed isolation network, the port-to-port isolation can be enhanced. The filtering PDs in [25] and [26] have been designed to extend the stopband bandwidth by using stepped-impedance coupled lines and the combination of a BPF and two lowpass filters, respectively. A four-way filtering PD comprising a pair of tri-mode resonators and three isolation resistors was presented in [27].

**FIGURE 1. Simplified architecture of a filtering diplexer-integrated PD.**

In the traditional approach to achieve frequency division, frequency selection, and power division functions, typically, a bandpass diplexer, which is composed of a three-port matching network and two different-frequency BPFs, cascaded directly with two PDs at the channel outputs (Fig. 1) are used. This architecture of the traditional in-series cascade solution requires five components, which increases the system size and cost. An effective approach to resolve the aforementioned problem is to integrate these components into a single device, namely a filtering diplexer-integrated PD (Fig. 1). The rapid development of RF and microwave communication technology has resulted in an increased demand for multifunction integrated diplexers. Although studies have been performed on the multifunction integrated diplexer design, problems of large circuit size, poor selectivity, and narrow stopband bandwidth persist [28]–[31]. In this study, novel multifunction integrated diplexers with frequency division, frequency selection, and power division functions were proposed. Realizable coupling structures for the multifunction integrated diplexer were provided. For demonstration, multifunction integrated diplexers with second-order and third-order band-pass responses were designed, fabricated, and measured. The proposed multifunction integrated diplexers have the advantages of a smaller circuit size, higher selectivity, and wider stopband bandwidth than other diplexers proposed in [28]–[31]. A good agreement was achieved between the simulation and measurement results, which verified the proposed design.

The remainder of the paper is organized as follows. In Sections 2 and 3, in addition to the detailed procedures for designing the multifunction integrated diplexers with second-order and third-order filtering responses, respectively, the theoretical analysis is presented. Moreover, the fabrication of two multifunction integrated diplexers using microstrip technology is presented for validation. The measurement results are presented and compared with the full-wave EM simulation results. In addition, the performance is compared with that of the reported diplexers, and the academic contributions of the proposed multifunction integrated diplexers are highlighted. Finally, the conclusion is presented in Section 4.

**FIGURE 2. Coupling structure of the proposed second-order multifunction integrated diplexer.**

**II. DESIGN OF THE SECOND-ORDER MULTIFUNCTION INTEGRATED DIPLEXER**

Fig. 2 illustrates the coupling structure of the proposed second-order multifunction integrated diplexer, which consists of two dual-mode resonators (resonators I and II) and two isolation resistors ($R_1$ and $R_2$), where $S$ and $L$ denote the input and output ports, respectively. The first odd-mode and even-mode resonance frequencies, namely, $f_{o1}^N$ and $f_{e1}^N$, of the dual-mode resonator were used to form the operating passband of the filtering diplexer for channel $N$ ($N = I, II$). The energy signal launched from the input port (port 1) passes through a dual-mode resonator to the output ports (ports 2 and 3 or ports 4 and 5). To realize equal-power division with the in-phase property for each channel, the output coupling structure should be symmetrical. Furthermore, to improve the impedance matching of the output ports and the isolation between the output ports for each channel, two resistors, namely $R_1$ and $R_2$, were connected between the outputs. The isolation resistors have a negligible influence on the equal-power splitting and filtering performances [18].

The dual-mode stub-loaded resonator [Fig. 3(a)] was selected to construct the second-order multifunction integrated diplexer. Here, $Z_t$ and $\theta_t$ represent the characteristic impedance and electric length of the transmission line, respectively. Due to the symmetric circuit structure of the
FIGURE 3. (a) Circuit model of the dual-mode stub-loaded resonator. (b) Even-mode and (c) odd-mode equivalent circuit models.

The resonance conditions of the dual-mode stub-loaded resonator can be analyzed using the even- and odd-mode equivalent circuits illustrated in Fig. 3(b) and (c), respectively. By setting $\text{Im}[Y_{\text{even}}] = 0$ and $\text{Im}[Y_{\text{odd}}] = 0$, the even- and odd-mode resonance conditions of the resonator can be calculated as follows:

$$Z_2 \cot \theta_1 = 2Z_1 \tan \theta_2$$  \hspace{1cm} (1)

$$\cot \theta_2 = 0$$  \hspace{1cm} (2)

Equation (2) indicates that the odd-mode resonant frequency $f_{o1}$ depends only on $\theta_2$. Therefore, in the design of the dual-mode stub-loaded resonator, the first step is to determine the odd-mode resonant frequency $f_{o1}$ by adjusting $\theta_2$. Next, the even-mode resonant frequency $f_{e1}$ can be determined by properly adjusting $\theta_1$, $Z_1$, and $Z_2$. Based on the resonance conditions, the design graph for the resonant frequency ratio $f_{e1}/f_{o1}$ with respect to $\theta_1/\theta_2$ can be obtained as displayed in Fig. 4. For example, if a $f_{e1}/f_{o1}$ value close to unity is required, the larger value of $Z_2/Z_1$ and the smaller value of $\theta_1/\theta_2$ should be selected.

FIGURE 4. Design graph of the dual-mode stub-loaded resonator in Fig. 3(a) as a function of $\theta_1/\theta_2$.

TABLE 1. Specification of the second-order multifunction integrated diplexer.

| Channel            | I     | II    |
|--------------------|-------|-------|
| Center frequency (GHz) | 1.525 | 2.125 |
| Fractional bandwidth (%) | 3.7   | 3     |
| Filter order       | 2     | 2     |
| Power division ratio | 1:1   | 1:1   |

To verify the design, a second-order multifunction integrated microstrip diplexer was designed and implemented. A Rogers RO4003C ($\varepsilon_r = 3.55$, $h = 0.508$ mm, and $\tan \delta = 0.0027$) was used as the dielectric substrate. The design specifications of the multifunction integrated diplexer are listed in Table 1. According to the given specifications, the coupling matrix can be synthesized as follows [32]:

$$[m]_N = \begin{bmatrix} 0 & m_{11} & m_{12} & m_{1L} \\ m_{1S} & m_{21} & m_{22} & m_{2L} \\ m_{LS} & m_{L1} & m_{L2} & 0 \end{bmatrix}$$

$$N = I, II$$

FIGURE 5. Theoretical circuit simulation result of the second-order multifunction integrated diplexer.

Fig. 5 shows the circuit simulation result of the multifunction integrated diplexer, which meet the prescribed specifications. The layout of the second-order multifunction integrated diplexer is displayed in Fig. 6. Resonators I and II are located at the bottom-right and bottom-left sides of the input feeding line, respectively, to ensure circuit compactness. The distributed coupling technique was adopted to integrate the two-channel filtering PDs in this design. The distributed
coupling structure indicates that the loading effects between channel passbands are small [33]. Thus, the two-channel passbands can be designed independently. The desired even- and odd-mode resonant frequencies of each dual-mode resonator can be derived as follows [34]:

\[
    f_{e1}^N = f_0^N \left(1 - \frac{m_{Si} \cdot \Delta f^N}{2 f_0^N}\right) \\
    f_{o1}^N = f_0^N \left(1 - \frac{m_{Si} \cdot \Delta f^N}{2 f_0^N}\right)
\]

where \( f_0^N \) and \( \Delta f^N \) are the center frequency and bandwidth of the passband for channel \( N \), respectively, and \( m_{Si} \) is the coupling coefficient (\( i = 1, 2 \)). Subsequently, the geometric dimensions of the dual-mode stub-loaded resonators can be determined using the following frequencies:

\[
    f_{e1}^I = 1.49 \text{ GHz} \; \quad f_{o1}^I = 1.56 \text{ GHz} \\
    f_{e1}^H = 2.09 \text{ GHz} \; \quad f_{o1}^H = 2.16 \text{ GHz}
\]

The input even- and odd-mode external quality factors can be calculated as follows [35]:

\[
    Q_{e,i,n} = \frac{m_{Si}}{\Delta f^N \cdot m_{Si}}, \quad i = 1, 2; \quad n = e, o1
\]

where \( m_{Si} \) represent the coupling coefficient between the source and resonator. Considering the case of equal-power division into two outputs for each channel, \( m_{Si}^L = m_{Si}^L = \frac{1}{\sqrt{2}} m_{Si} \), and the output external quality factor should be twice as much as the input quality factor. According to the specification in Table 1, the input external quality factors were as follows:

\[
    Q_{e,i,1}^I = 42.6; \quad Q_{e,i,o1}^I = 64.6 \\
    Q_{e,i,1}^H = 52.5; \quad Q_{e,i,o1}^H = 79.7
\]

The desired external quality factor of the second-order multifunction integrated diplexer is defined as the arithmetic average of even- and odd-mode external quality factors. Thus,

\[
    Q_e^N = \left( Q_{e,i,1}^N + Q_{e,o1}^N \right) / 2.
\]

To satisfy the desired external quality factors, structural parameters such as the line length, line width, and gap of the I/O coupled lines are properly adjusted. The external quality factor can be calculated using the following equation [35]:

\[
    Q_e = \omega_0 \tau_d (\omega_0) / 4
\]

where \( \tau_d (\omega_0) \) is the group delay of \( S_{11} \) at resonance frequency \( \omega_0 \).

To enhance the impedance matching for ports 2–5 and the isolation between the output ports for each channel, two resistors, namely \( R_1 \) and \( R_2 \), were introduced at the open ends of the output transmission lines (Fig. 6). According to the design principle of PDs, the isolation is determined based on the matching conditions of the PD. In this design, since the output coupled-line section is used to realize an equal-split filtering response, the resistance of the isolation resistor is the only parameter to control the isolation [13], [18]. Therefore, the resistances of the two resistors were properly adjusted to achieve high isolation and impedance matching. The variation of the resistances did not have an effect on the equal-power splitting and filtering performances. The simulated output return losses (\(|S_{22}|\), \(|S_{33}|\), \(|S_{44}|\), and \(|S_{55}|\)) and isolation (\(|S_{32}|\) and \(|S_{41}|\)) with variation in \( R_1 \) and \( R_2 \) are displayed in Fig. 7(a) and (b). Improved isolation and impedance matching were achieved for \( R_1 = R_2 = 100 \Omega \). The isolation resistor can be loaded at the other positions between the output feeding lines. However, once the location of the isolation resistor is changed, the resistance should be re-evaluated to achieve a satisfactory isolation and impedance matching performance.

![FIGURE 7. Simulated output return loss and isolation performances with varied \( R_1 \) and \( R_2 \) for (a) channel I and (b) channel II.](image-url)
at 1.525 GHz. The full-wave EM simulation is performed using Keysight Advanced Design System (ADS), and measurement is accomplished using the Agilent N5230A network analyzer. Figs. 10–12 depict the EM simulated and measured results of the proposed second-order multifunction integrated diplexer. The diplexer provided a second-order filtering function with equal-power division for each channel. The measurement results revealed that the return losses ($|S_{11}|$, $|S_{22}|$, $|S_{33}|$, and $|S_{55}|$) were $> 17$ dB and the insertion losses at the channel passbands I and II ($|S_{21}|$ and $|S_{41}|$) including the 3-dB equal-power division loss were approximately ($3 + 1.2$) and ($3 + 1.6$) dB, respectively, with the amplitude imbalances ($|S_{21}| - |S_{31}|$ and $|S_{41}| - |S_{51}|$) $< 0.1$ dB. The isolations between the output ports ($|S_{32}|$ and $|S_{54}|$) were $> 30$ dB and $> 23$ dB over the entire channel passbands I and II, respectively. The port isolations between various channels ($|S_{24}|$, $|S_{25}|$, $|S_{34}|$, and $|S_{35}|$) were $> 40$ dB. Furthermore, the in-band phase imbalances ($\angle S_{21} - \angle S_{31}$ and $\angle S_{41} - \angle S_{51}$) were within 0.2°. Fig. 12 displays the wideband response of the multifunction integrated diplexer and demonstrates the spurious frequency output of the multifunction integrated diplexer. The first spurious frequency appeared at approximately 4.5 GHz, which is the second even-mode resonance frequency of the dual-mode stub-loaded resonator I. The multifunction integrated diplexer had a wide stopband bandwidth and a spurious free range that was approximately three times the center frequency of channel I.

III. DESIGN OF THE THIRD-ORDER MULTIFUNCTION INTEGRATED DIPLEXER

Fig. 13 illustrates the coupling structure of the proposed third-order multifunction integrated diplexer, which is mainly composed of two tri-mode resonators (resonators I and II) and two isolation resistors ($R_1$ and $R_2$), where $S$ and $L$ denote the input and output ports, respectively. The first odd-mode and the first two even-mode resonance frequencies ($\omega_{01}$, $\omega_{02}$, and $\omega_{03}$) of the tri-mode resonator were used to form the operating passband of the filtering diplexer for channel $N$ ($N = I, II$). The energy signal from the input port (port 1) to the output ports (ports 2 and 3 or ports 4 and 5) passed through a single tri-mode resonator for each channel. The symmetrical output feeding structure that formed provided an equal-power division with the in-phase property for each channel. Furthermore, two resistors, namely $R_1$ and $R_2$, were added between the outputs to enhance the impedance matching of the output ports and the isolation between output ports for each channel.
The tri-mode stub-loaded resonator [Fig. 14(a)] was selected to construct the third-order multifunction integrated diplexer. Because of the symmetrical nature of the tri-mode stub-loaded resonator, the resonance conditions can be analyzed using the even- and odd-mode equivalent circuits as illustrated in Fig. 14(b) and (c), respectively. From \( \text{Im}\left[ Y_{\text{even}} \right] = 0 \) and \( \text{Im}\left[ Y_{\text{odd}} \right] = 0 \), we can obtain the following even- and odd-mode resonance conditions of the resonator:

\[
Z_2(\cot\theta_1 - \tan\theta_3) = 2Z_1\tan\theta_2 \tag{12}
\]

\[
\cot\theta_2 = 0 \tag{13}
\]

The design steps of the tri-mode stub-loaded resonator are as follows. First, determine \( f_{o1} \) by properly adjusting \( \theta_2 \). According to (13), \( f_{o1} \) only depends on \( \theta_2 \). Second, determine \( f_{e1} \) and \( f_{e2} \) by properly adjusting \( Z_1, Z_2, \theta_1, \) and \( \theta_3 \), with \( f_{o1} \) unchanged. Fig. 15(a)–(c) indicate that the smaller \( \theta_1 \) and \( \theta_3 \) are, the larger \( f_{e1}/f_{o1} \) and \( f_{e2}/f_{o1} \) as \( Z_2/Z_1 \) are. Moreover, \( f_{e1}/f_{o1} \) and \( f_{e2}/f_{o1} \) are mainly influenced by \( \theta_1 \) and \( \theta_3 \), respectively. Therefore, by properly varying the physical dimensions of the tri-mode stub-loaded resonator, the first three resonance frequencies (i.e., \( f_{o1}, f_{e1}, \) and \( f_{e2} \)) can then be flexibly determined.

### TABLE 3. Specification of the third-order multifunction integrated diplexer.

| Channel | I | II |
|---------|---|----|
| Center frequency (GHz) | 1.415 | 2.02 |
| Fractional bandwidth (%) | 6.4 | 5 |
| Filter order | 3 | 3 |
| Power division ratio | 1:1 | 1:1 |

For demonstration, a third-order multifunction integrated microstrip diplexer was designed and implemented. A Rogers RO4003C (\( \varepsilon_r = 3.55, h = 0.508 \text{ mm}, \) and \( \tan \delta = 0.0027 \)) was used as the dielectric substrate. The design specification of the multifunction integrated diplexer is listed in Table 3.
According to given specification, the coupling matrix can be synthesized as follows [32]:

\[
[M]^N = \begin{bmatrix}
0 & m_{S1} & m_{S2} & m_{S3} & m_{SL} \\
m_{1S} & m_{11} & m_{12} & m_{13} & m_{1L} \\
m_{2S} & m_{21} & m_{22} & m_{23} & m_{2L} \\
m_{3S} & m_{31} & m_{32} & m_{33} & m_{3L} \\
m_{LS} & m_{L1} & m_{L2} & m_{L3} & 0
\end{bmatrix}
\]

\[N = I, II\]
(14)

Each tri-mode resonator can be derived, respectively, as follows [36]:

\[
f_{c1} = \frac{f_0}{2} \cdot \left[ -\frac{\Delta f^N}{f_0^N} m_{11} + \sqrt{\left(\frac{\Delta f^N}{f_0^N} m_{12}\right)^2 + 4} \right]
\]
(15)

\[
f_{o1} = \frac{f_0}{2} \cdot \left[ -\frac{\Delta f^N}{f_0^N} m_{22} + \sqrt{\left(\frac{\Delta f^N}{f_0^N} m_{22}\right)^2 + 4} \right]
\]
(16)

\[
f_{c2} = \frac{f_0}{2} \cdot \left[ -\frac{\Delta f^N}{f_0^N} m_{33} + \sqrt{\left(\frac{\Delta f^N}{f_0^N} m_{33}\right)^2 + 4} \right]
\]
(17)

where \(f_0^N\) and \(\Delta f^N\) are the center frequency and bandwidth of the passband for channel \(N\), respectively, and \(m_i\) is the coupling coefficient \((i = 1, 2, 3)\). The geometric dimensions of the tri-mode stub-loaded resonators can then be determined according to the following derived frequencies:

\[
f_{c1}^I = 1.35 \text{ GHz}; \quad f_{c1}^H = 1.43 \text{ GHz};
\]
(18)

\[
f_{c2}^I = 1.48 \text{ GHz}; \quad f_{c2}^H = 1.95 \text{ GHz};
\]
(19)

\[
f_{o1}^I = 2.03 \text{ GHz}; \quad f_{o1}^H = 2.09 \text{ GHz};
\]

For equal-power division into two outputs for each channel, the output external quality factor should be twice as much as the input quality factors. The input even- and odd-mode external quality factors can be calculated by using the following equation:

\[
Q_{e,n}^N = \frac{f_0^N}{\Delta f^N \cdot m_{Si}^2}, \quad i = 1, 2, 3; \quad n = e1, o1, e2
\]
(20)

and gives

\[
Q_{c1,e1} = 43.7; \quad Q_{c1,o1} = 26.8; \quad Q_{c2,e2} = 69.5
\]
(21)

\[
Q_{c1,e1} = 56.1; \quad Q_{c2,o1} = 34.5; \quad Q_{c2,e2} = 89.3
\]
(22)

The desired external quality factor of the third-order multifunction integrated diplexer is defined as the average value of external quality factors (i.e., \(Q_e^N = (Q_{e,e1}^N + Q_{e,o1}^N + Q_{e,e2}^N)/3\)). Subsequently, the line length, line width, and gap of the I/O coupled lines were properly adjusted to satisfy the desired external quality factor extracted by using (11).

To enhance the impedance matching of output ports and the isolation between output ports for each channel, two resistors, namely \(R_1\) and \(R_2\), were loaded at the open ends of the output feeding lines, as displayed in Fig. 17. Furthermore, the resistances of the two resistors were appropriately tuned to achieve high isolation and good impedance matching. The simulated output return losses (\(|S_{22}|, |S_{33}|, |S_{44}|\), and \(|S_{53}|\) and isolation (\(|S_{22}|\) and \(|S_{44}|\)) with varied \(R_1\) and \(R_2\) are displayed in Fig. 18(a) and (b). Excellent
isolation and impedance matching can be acquired when $R_1 = R_2 = 100$ $\Omega$.

The current distributions of the third-order multifunction integrated diplexer at two-channel frequencies are illustrated in Fig. 19(a) and (b). The loading effects between channel passbands were small and each passband of the multifunction integrated diplexer could be independently designed.

The physical dimensions of the multifunction integrated diplexer were determined, as listed in Table 4, according to the aforementioned design procedure. Fig. 20 is a photograph of the third-order multifunction integrated diplexer. The circuit size was $0.42 \lambda_g \times 0.25 \lambda_g$ (58.5 mm $\times$ 34.8 mm), where $\lambda_g$ is the guided wavelength at 1.415 GHz. Figs. 21–23 present the simulated and measured results of the proposed third-order multifunction integrated diplexer. The diplexer provided a third-order filtering function with equal-power division for each channel.
The measurement results revealed that the return losses ($|S_{11}|$, $|S_{22}|$, $|S_{33}|$, $|S_{44}|$, and $|S_{55}|$) were greater than 15 dB and the insertion losses at the channel passbands I and II ($|S_{21}|$ and $|S_{41}|$) including the 3-dB equal-power division loss were approximately (3.1 + 1.4) and (3.1 + 1.6) dB, respectively, with the amplitude imbalances ($|S_{21}| - |S_{31}|$ and $|S_{41}| - |S_{51}|$) less than 0.1 dB. The isolations between the output ports ($|S_{32}|$ and $|S_{54}|$) were greater than 32 dB and greater than 29 dB over the entire channel passbands I and II, respectively. The port isolations between various channels ($|S_{24}|$, $|S_{25}|$, $|S_{34}|$, and $|S_{35}|$) were all greater than 46 dB. Furthermore, the in-band phase imbalances ($\angle S_{21} - \angle S_{31}$ and $\angle S_{41} - \angle S_{51}$) were within 0.1°. In addition, an inherent transmission zero (TZ) occurred at the upper side of passband for each channel, which increased frequency selectivity. The TZ was generated when the stub was loaded on the central plane of the resonator at quarter-wavelength resonance [33], [34].

Fig. 23 displays the wideband response of the multifunction integrated diplexer. The first spurious frequency occurred at approximately 4.4 GHz, which is the third even-mode resonance frequency of the tri-mode stub-loaded resonator I. The multifunction integrated diplexer exhibited a wide stopband bandwidth with an attenuation of greater than 40 dB up to approximately $3f_0$.

To highlight the academic contributions of this work, the benefits of the proposed multifunction integrated diplexers are summarized as follows.

A. MULTIPLE FUNCTIONS
The traditional diplexers could just provide the functions of frequency division and frequency selection. However, the new multifunctional diplexer in this work could further provide the functions of frequency division, frequency selection, and power splitting without a significant increase in size.

B. HIGH INTEGRATION
Integrating multiple functions into a single device is an effective method to reduce circuit size and cost. As compared to the traditional cascaded configuration of a power-divider diplexer, the proposed integrated configuration of a power-divider diplexer has not only saved several resonator spaces, but also saved the space of the matching circuit. Moreover, since the two different-frequency PDs are integrated into a diplexer, the circuit-size reduction of more than 70% can be achieved.

| TABLE 5. Comparison with the related circuits. |
|-----------------------------------------------|
| Design | CF (GHz) | FBW (%) | FO | IL (dB) | Iso (dB) | Stopband attenuation | Size ($2L^2$) |
|-------|---------|--------|----|--------|---------|---------------------|-------------|
| -I    | 1.525, 2.125 | 3.7, 3 | 2 | 4.2, 4.6 | > 23 | 40 dB ($3f_0$) | 0.098 |
| -II   | 1.413, 2.02 | 6.4, 5 | 3 | 4.4, 4.6 | > 29 | 40 dB ($3f_0$) | 0.105 |
| [28]  | 1.77, 2.4 | Not reported | | 2 | 3.7, 4 | > 20 | 20 dB ($< 2f_0$) | 0.3 |
| [29]  | 2.5, 3 | Not reported | | 2 | 4.6, 4.9 | > 21 | 25 dB ($2f_0$) | 0.2 |
| [30]  | 1.1, 1.15 | 3.5, 3.6 | 2 | 3.7, 3.8 | > 28 | 40 dB ($2f_0$) | 0.26 |
| [31]  | 1.8, 2.4 | 6.3, 6.3 | 2 | 4.8, 4.8 | > 20 | 40 dB ($2f_0$) | 0.8 |

CF, center frequency; FBW, fractional bandwidth; FO, filter order; IL, insertion loss; Iso, isolation

C. SUPERIOR PERFORMANCE IN TERMS OF COMPACT SIZE, HIGH FREQUENCY SELECTIVITY, LARGE STOPBAND ATTENUATION, AND WIDE STOPBAND BANDWIDTH
The proposed design was compared with state-of-the-art diplexers (Table 5). In [28] and [31], the duplexing filtering PDs using integrated matching circuits were proposed. However, the circuit configurations are large. Furthermore, the matching circuits are complex. In [29], a dual-mode PD diplexer with a second-order passband response was proposed. However, the diplexer consists of two pairs of dual-mode resonators, resulting in a bulky circuit size. The diplexer-integrated filtering PD in [30] commonly has a large circuit size because eight resonators are required for coupling. Furthermore, because all circuits in [28]–[31] have been designed with second-order filtering response, the selectivity is not satisfactory. In this study, a novel and simple design for the multifunction integrated diplexer with a smaller circuit...
size, higher selectivity, larger stopband attenuation, and wider stopband bandwidth was proposed.

**IV. CONCLUSION**

In this study, a novel multifunction integrated diplexer with frequency division, frequency selection, and equal-power division functions was developed. Second-order and third-order multifunction integrated diplexers were designed and implemented for verification. The experimental results demonstrated that the proposed multifunction integrated diplexers exhibited a compact size, high selectivity, high port-to-port isolation, and favorable out-of-band performance with 40-dB stopband attenuation, which is up to three times the center frequency of the diplexer.

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