High-Selection Bandpass Filter Based on Two Merged Ring Resonators

Xiao-yu WENG 1, Kai-da XU 1, 2, Ying-jiang GUO 3, An-xue ZHANG 1, Qiang CHEN 2

1 School of Information and Communications Engineering, Xi’an Jiaotong University, Xi’an 710049, China
2 Dept. of Communications Engineering, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan
3 Microsystem and Terahertz Research Center, China Academy of Engineering Physics, Chengdu 610200, China

kaidaxu@ieee.org

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Abstract. A high-selection bandpass filter (BPF) based on two merged ring resonators is presented in this paper. The structure of this proposed BPF can be seen as the two one-wavelength ring resonators merged each other by sharing the common \( \frac{\lambda_g}{2} \) microstrip line. Due to symmetric structure, it can be analyzed by even- and odd-mode method and the locations of six transmission zeros are calculated using input impedance deductions. For further demonstration, a BPF example centered at 2 GHz is fabricated with high frequency selectivity. The measured 3-dB fractional bandwidth is 11% (1.89–2.11 GHz) and insertion loss is less than 2 dB in the passband. Good agreement between simulation and measurement verifies the feasibility of the design method.

Keywords
Bandpass filter, coupled-line structures, high selectivity, transmission zeros

1. Introduction

In the modern wireless communication systems, high-performance bandpass filters (BPFs) with low insertion loss in the passband and high out-of-band suppression are extremely desirable. In recent years, numerous different methods for designing high-performance BPFs have been presented, such as using coupled line structures [1], [2], ring resonators [3], [4], spoof surface plasmon polaritons [5], [6], transversal signal-interference techniques [7]. In [1], a compact seventh-order wideband BPF with sharp roll-off skirts using coupled lines and open/shorted stubs is proposed. The open/shorted stubs are utilized to introduce more transmission zeros (TZs) and acquire better performance in the stopband. In [3], a dual-mode ring resonator fed by quarter-wavelength side-coupled lines is analyzed. The resonator synthesis is developed to calculate the center frequency, bandwidth, TZs and insertion loss. In [7], transversal signal-interference concept is utilized that employing two different transmission paths for the BPF. And the TZs were generated when the two paths are out-of-phase. But this method is at the expense of a large circuit size. Besides, several novel structures are introduced to achieve higher performance, such as two pairs of twist modified split-ring resonators [8] and stepped impedance open-stub loaded ring resonator [9].

In this paper, a BPF based on two merged ring resonators with high selectivity is proposed, which is quite different from the BPF using ring resonators in [10]. Due to the symmetric structure of this proposed BPF, the distributions of six TZs can be calculated by odd- and even-mode method. The theoretical derivation of the proposed BPF is demonstrated. For validation, a BPF example centered at 2 GHz is fabricated and measured.

2. Design and Analysis of the Proposed BPF

The ideal circuit of the proposed BPF, which consists of two pairs of coupled lines and five microstrip lines, is shown in Fig. 1(a). The filter structure can be seen as the two one-wavelength (\( \lambda_g \)) ring resonators merged each other with \( \frac{\lambda_g}{2} \) merged length in the middle and \( \frac{\lambda_g}{4} \) coupled to input and output feedlines. Due to symmetry of this BPF structure, it can be analyzed by even- and odd-mode equivalent circuits as illustrated in Fig. 1(b) and (c), respectively.

Observed from Fig. 1(b), the following equation can be established [11],

\[
\begin{bmatrix}
V_1^e \\
V_2^e \\
V_3^e \\
V_4^e \\
V_5^e \\
V_6^e
\end{bmatrix} =
\begin{bmatrix}
Z_{11}^e \\
Z_{12}^e \\
Z_{13}^e \\
Z_{14}^e \\
Z_{15}^e \\
Z_{16}^e
\end{bmatrix}
\begin{bmatrix}
I_1^e \\
I_2^e \\
I_3^e \\
I_4^e \\
I_5^e \\
I_6^e
\end{bmatrix}
\]

(1)

where \( [Z]^e \) and \( [Z]^o \) denote 4×4 and 2×2 impedance matrices of the circuit network in dash box, \( V_n^e \) and \( I_n^e \) denote the voltage and current of the corresponding \( n \)th port, respectively.
The impedance matrix of the coupled line $[Z]^a$ can be expressed by

$$[Z]^a = \begin{bmatrix} Z_{11}^a & Z_{12}^a & Z_{13}^a & Z_{14}^a \\ Z_{21}^a & Z_{22}^a & Z_{23}^a & Z_{24}^a \\ Z_{31}^a & Z_{32}^a & Z_{33}^a & Z_{34}^a \\ Z_{41}^a & Z_{42}^a & Z_{43}^a & Z_{44}^a \end{bmatrix}$$ \hspace{1cm} (2a)$$

where

$$Z_{11}^a = Z_{22}^a = Z_{33}^a = Z_{44}^a = -\frac{1}{2}(Z_{0e} + Z_{0o})\cot \theta , \hspace{1cm} (2b)$$

$$Z_{12}^a = Z_{21}^a = Z_{34}^a = Z_{43}^a = -\frac{1}{2}(Z_{0e} + Z_{0o})\csc \theta , \hspace{1cm} (2c)$$

$$Z_{13}^a = Z_{23}^a = Z_{32}^a = Z_{42}^a = -\frac{1}{2}(Z_{0e} - Z_{0o})\cot \theta , \hspace{1cm} (2d)$$

$$Z_{14}^a = Z_{24}^a = Z_{31}^a = Z_{41}^a = -\frac{1}{2}(Z_{0e} - Z_{0o})\csc \theta . \hspace{1cm} (2e)$$

On the other hand, the impedance matrix $[Z]^b$ can be expressed by:

$$[Z]^b = \begin{bmatrix} Z_{11}^b & Z_{12}^b \\ Z_{21}^b & Z_{22}^b \end{bmatrix} . \hspace{1cm} (3a)$$

Seen from Fig. 1(b), the network with impedance matrix $[Z]^b$ is constituted by two connected microstrip lines. The voltage and current of the two connected microstrip lines can be determined [11]:
\[ B = \begin{bmatrix}
Z_{11}^* & Z_{12}^* & Z_{13}^* & Z_{14}^* \\
Z_{21}^* & Z_{22}^* + Z_{a1} & Z_{23}^* & Z_{24}^* \\
Z_{31}^* & Z_{32}^* & Z_{33}^* + Z_{B2} & Z_{34}^* \\
Z_{41}^* & Z_{42}^* & Z_{43} & Z_{44}^* 
\end{bmatrix}, \quad (6b) \]

\[ Z_{B1} = jZ_{j} \tan \theta, \quad (6c) \]

\[ Z_{B2} = jZ_{j} \tan \theta. \quad (6d) \]

Therefore, the reflection coefficient \( S_{11} \) and transmission coefficient \( S_{21} \) of the proposed BPF can be calculated as [11]:

\[ S_{11} = \frac{\Gamma_{e} + \Gamma_{o}}{2} = \frac{Z_{inc}Z_{ina} - Z_{0}^{2}}{(Z_{inc} + Z_{0})(Z_{ina} + Z_{0})}, \quad (7a) \]

\[ S_{21} = \frac{\Gamma_{e} - \Gamma_{o}}{2} = \frac{Z_{o}(Z_{inc} - Z_{ina})}{(Z_{inc} + Z_{0})(Z_{ina} + Z_{0})}. \quad (7b) \]

Figure 2(a) shows the calculated responses by MATLAB and simulated responses by ADS software of the proposed BPF, where \( Z_{0e} = 185 \, \Omega \), \( Z_{0o} = 98 \, \Omega \), \( Z_{1} = 50 \, \Omega \), \( Z_{2} = 92 \, \Omega \), \( Z_{3} = 80 \, \Omega \) and \( \theta = 90^\circ \). The simulation results using ADS agree well with the theoretical deductions. Seen from Fig. 2(a), there are five transmission poles in the pass-band and six TZs (\( f_{tz1}, f_{tz2}, f_{tz3}, f_{tz4}, f_{tz5}, \) and \( f_{tz6} \)) in the stop-band ranging from 0 to \( 2f_{0} \), where \( f_{0} \) denotes the center frequency of the proposed BPF. These TZs can be determined by setting \( S_{21} = 0 \), and the calculated results are shown below:

\[ f_{u1} = 0, f_{u2} = 2f_{0}, \quad (8a) \]

\[ f_{u2} = 2f_{0} \cos^{-1} \left( \frac{Z_{inc}B + \sqrt{C}}{4A} \right), \quad f_{u5} = 2f_{0} - f_{u2}, \quad (8b) \]

\[ f_{u3} = 2f_{0} \cos^{-1} \left( \frac{Z_{inc}B - \sqrt{C}}{4A} \right), \quad f_{u4} = 2f_{0} - f_{u3} \quad (8c) \]

where

\[ A = 8(Z_{0e}^{2} + Z_{0o}^{2})(Z_{1} + Z_{2}) + 4Z_{2}Z_{3}(Z_{1} + Z_{2})(Z_{0e} + Z_{0o}) + 4Z_{2}Z_{3}[Z_{0e}Z_{1} + Z_{0o}Z_{2} - 2Z_{2}Z_{0e}Z_{0o} + Z_{1}Z_{2}(Z_{0e} + Z_{0o})] + Z_{2}Z_{3}[Z_{0e}Z_{1} + Z_{0o}Z_{2}] + 2Z_{1}(Z_{0e} - Z_{0o})^{2}, \quad (8d) \]

\[ B = (Z_{0e} + Z_{0o})^{2} + 4Z_{2}^{2} \]

\[ + 4[(Z_{0e} - Z_{0o})^{2} + 2(Z_{0e} + Z_{0o})Z_{1}]Z_{3} \]

\[ + 4(4Z_{1} - Z_{0e} - Z_{0o})Z_{2}Z_{3} + 8(Z_{0e} + Z_{0o} - 2Z_{2})Z_{0e}Z_{0o}, \quad (8e) \]

\[ C = D + Z_{1}(8E + 16Z_{2}F) - 64 \frac{Z_{2}}{Z_{2}}[Z_{0e}Z_{0o}(Z_{0e} + Z_{0o})]^{2}, \quad (8f) \]

\[ D = (4Z_{1} + Z_{2})^{2}(Z_{0e} - Z_{0o})^{4} + 16[8Z_{1}(2Z_{2} - Z_{1}) - Z_{1}^{2}](Z_{0e}Z_{0o})^{2} \]

\[ - 16[4(Z_{1}(2Z_{2} + Z_{1}) + 2Z_{2}Z_{0e}Z_{0o} - Z_{1})] \]

\[ - (2Z_{1} + Z_{2})(Z_{0e} + Z_{0o})^{2}]Z_{0e}Z_{0o}(Z_{0e} + Z_{0o}), \quad (8g) \]

\[ E = \left\{ (20Z_{1} + 4Z_{2} + Z_{1})(Z_{0e}Z_{0o}) + (4Z_{1} + Z_{2})(2Z_{1} + Z_{2})(Z_{0e} + Z_{0o}) + \right\} \]

\[ [Z_{2}(4Z_{1} + Z_{2})(4Z_{1} + 3Z_{2}) + 8Z_{1}Z_{3}]^{2}(Z_{0e} + Z_{0o})^{2}, \quad (8h) \]

\[ F = Z_{2}Z_{1}(4Z_{1} + Z_{2})^{2} - 8(Z_{1} + Z_{2})(4Z_{1} + Z_{2})Z_{0e}Z_{0o} + 2Z_{2}(2Z_{1} + Z_{2})(4Z_{1} + Z_{2})(Z_{0e} + Z_{0o}). \quad (8i) \]
3. Implementation Results

For demonstration, an example of the proposed BPF centered at 2 GHz is designed and fabricated. The physical dimensions of the coupled lines and those of the microstrip lines can be extracted from the corresponding electrical lengths and characteristic impedances. These dimensions of the BPF are further fine-tuned in full-wave electromagnetic simulation software Ansys HFSS to consider the unintended coupling effect. The layout of the proposed filter and its final dimensions are shown in Fig. 3(a). Figure 3(b) illustrates the photograph fabricated on a F4B substrate with relative dielectric constant of $\varepsilon_r = 2.65$ and thickness of $h = 1$ mm. The occupied size of this filter is approximately $49.5 \times 30.5$ mm$^2$, i.e., $0.49\lambda_g \times 0.30\lambda_g$, where $\lambda_g$ is the guided wavelength of 50 $\Omega$ microstrip line at 2 GHz.

### Table 1. Performance comparisons with some previous BPFs (*NM: Not Mentioned)

| $f_0$ (GHz) | FBW (%) | Number of TZs | $\frac{S_{11}}{S_{21}}$ (dB) | $\varepsilon_r$ | $h$ | $\lambda_g$ | $\lambda_d$ |
|-------------|---------|---------------|-----------------|-------------|-----|---------|------------|
| [4]         | 3.2     | 20.6          | 6               | 2.2 / 12.5  | $\varepsilon_r = 2.65$, $h = 1$ mm | 0.75 × 0.43 | 1.06 × 0.61 |
| [8]         | 2.1     | 19            | 8               | 1.8 / 12    | $\varepsilon_r = 2.65$, $h = 1$ mm | 0.26 × 0.19 | 0.39 × 0.28 |
| [13]        | 4.5     | 60            | 2               | 1.6 / 10    | $\varepsilon_r = 4.4$, $h = 0.8$ mm | 0.18 × 0.06 | 0.28 × 0.09 |
| [14]        | 2.6     | 3             | 1               | 1.8 / 10    | $\varepsilon_r = 10.7$, $h = 1.27$ mm | 0.16 × 0.09 | 0.42 × 0.25 |
| [15]        | 3.35    | 6             | 2               | 2.4 / NM*   | NM          | 0.12 × 0.09 |            |
| [16]        | 1.68    | 4             | 2               | 1.3 / 22    | $\varepsilon_r = 10.8$, $h = 1.27$ mm | 0.21 × 0.63 |            |
| This work   | 2       | 11            | 5               | 2 / 15      | $\varepsilon_r = 2.65$, $h = 1$ mm | 0.330 × 0.203 | 0.49 × 0.30 |

*Fig. 2.* Calculated responses by MATLAB and simulated responses by ADS of the proposed BPF, where $Z_{in} = 185 \Omega$, $Z_{in} = 98 \Omega$, $Z_1 = 50 \Omega$, $Z_2 = 92 \Omega$, $Z_3 = 80 \Omega$, (a) calculated $f_0/f_2$ and the 3-dB FBW versus $Z_1$, (c) simulated $S_21$ versus $Z_2$, where $Z_{in} = 185 \Omega$, $Z_{in} = 98 \Omega$, $Z_1 = 50 \Omega$, $Z_2 = 80 \Omega$, (d) calculated $f_0/f_e$ versus $Z_0$, where $Z_{in} = 185 \Omega$, $Z_{in} = 98 \Omega$, $Z_1 = 50 \Omega$, $Z_2 = 92 \Omega$. Obviously, the two TZs $f_{t1}$ and $f_{t6}$ are constant, located at 0 and $2f_{in}$, respectively. When $Z_{in} = 185 \Omega$, $Z_{in} = 98 \Omega$ and $Z_1 = 50 \Omega$ are fixed, the other TZs ($f_{t2}$, $f_{t3}$, $f_{t4}$, $f_{t5}$) are relevant to the characteristic impedances $Z_2$ and $Z_3$. Figure 2(b) indicates the ratio of $f_0$ to $f_2$ and 3-dB fractional bandwidth (FBW) versus $Z_2$. As the characteristic impedance $Z_2$ shifts, $f_{t1}$ and $f_{t6}$ keep fixed, $f_{t2}$ and $f_{t4}$ are almost unchanged, whereas $f_{t3}$ and $f_{t5}$ will be adjusted. To illustrate more clearly, the $S_{21}$ simulation results with different values of $Z_2$ are shown in Fig. 2(c). It can be seen that the 3-dB FBW will be broadened with the decrease of $Z_2$. The minimum 3-dB FBW will be approached when $Z_2$ increases to 105 $\Omega$ under the rejection condition of over 10 dB at the stopband. In contrast, as depicted in Fig. 2(d), the locations of $f_{t2}$ and $f_{t3}$ will be moved rather than $f_{t3}$ and $f_{t4}$, as the characteristic impedance $Z_3$ is changed.
The simulated and measured $S_{11}$ and $S_{21}$ are shown in Fig. 4, which agree reasonably well with each other. The measured insertion loss is less than 2 dB, and the return loss is better than 15 dB within the passband from 1.89 to 2.11 GHz (3-dB FBW of 11%). Moreover, the measured rejection levels are over 14 dB at lower stopband from 0 to 1.87 GHz and better than 15 dB at upper stopband from 2.19 to 5 GHz. The performance comparisons with several reported BPFs are shown in Tab. 1.

4. Conclusion

A high-selectivity BPF based on two merged ring resonators has been presented in this paper. Due to the characteristics of the ring structure, six transmission zeros are generated. Through analysis and calculation procedure, the location of TZs is adjustable with change of microstrip line width, which provides an additional measure to narrow the stopband. However, the presented structure provides the improved performance in the stopband with the relatively more occupation. However, the size of this filter is hardly decreased due to the width of the microstrip line with $\lambda_g/2$ length in the middle. It is difficult to obtain more compact structure by folding the microstrip lines without affecting the frequency response. The proposed BPF can offer an alternative design idea for the application in the modern RF and wireless communication systems.

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About the Authors ...

Xiao-yu WENG was born in Henan, China. He received the B.E. degree in Xi’an Jiaotong University, Xi’an, China, in 2020, where he is currently working toward the M.E. degree. His research interests include RF/microwave components and circuits.

Kai-da XU was born in Zhejiang, China. He received the B.E. and Ph.D. degrees in Electromagnetic Field and...
Microwave Technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2009 and 2015, respectively. From 2012 to 2014, he was a Visiting Researcher with the Department of Electrical and Computer Engineering, Duke University, Durham, NC, USA. In 2015, he joined the Department of Electronic Science, Xiamen University, Xiamen, China as an Assistant Professor. From 2016 to 2017, he was a Post-doctoral Fellow with the State Key Laboratory of Millimeter Waves, City University of Hong Kong, Hong Kong. From 2018 to 2019, he was an Honorary Fellow with the Department of Electrical and Computer Engineering, University of Wisconsin–Madison, WI, USA. He was successfully selected into the “Youth Talent Support Program” of Xi’an Jiaotong University (XJTU) in May 2019, and joined the School of Information and Communications Engineering in XJTU in January 2020. Also, he was awarded a fellowship from the Japan Society for the Promotion of Science (JSPS) and joined the Department of Communications Engineering, Graduate School of Engineering, Tohoku University, as the JSPS Fellow in November 2019. He has authored and coauthored over 100 papers in peer-reviewed journals and over 40 papers in conference proceedings. He received the UESTC Outstanding Graduate Awards in 2009 and 2015, respectively. He was the recipient of National Graduate Student Scholarship in 2012, 2013, and 2014 from the Ministry of Education, China. Since 2017, he has served as an Associate Editor for both of the IEEE Access and Electronics Letters. He is also an Editorial Board Member of the AEÜ-International Journal of Electronics and Communications. His current research interests include RF/microwave, mm-wave/THz devices and antenna arrays.

**Ying-jiang GUO** was born in Sichuan, China. He received the B.E. and Ph.D. degrees in Electronic Engineering from the Sichuan University and University of Electronic Science and Technology in China, Chengdu, China in 2008 and 2018, respectively. From 2011 to 2013, he was with the Huawei Technologies Co., Ltd., where he was involved in the research of 5G communication prototype design. From 2013 to 2014, he was with the Sichuan Normal University, where he was a lecturer. Since 2018, he has been with Microsystem and Terahertz Research Center in China Academy of Engineering Physics as an assistant research fellow and focuses on the terahertz integrated circuits and communication technologies. He has authored or co-authored over 30 journal and conference papers. He holds over 5 patents in wireless communication. His research interests include the RF/microwave/mm-wave integrated circuits, THz modules/antennas, and systems in package.

**An-xue ZHANG** received the B.S. degree in Electrical Engineering from Henan Normal University in 1996 and the M.S. and Ph.D. degrees in Electromagnetic and Microwave Engineering from Xi’an Jiaotong University in 1999 and 2003, respectively. He is currently a Professor with Xi’an Jiaotong University. His main research fields include antenna and electromagnetic wave propagation, RF and microwave circuit design, and metamaterials.

**Qiang CHEN** received the B.E. degree in Electrical Engineering from Henan Normal University in 1996 and the M.S. and Ph.D. degrees in Electromagnetic and Microwave Engineering from Xi’an Jiaotong University in 1999 and 2003, respectively. He is currently a Professor with Xi’an Jiaotong University. His main research fields include RF/microwave, mm-wave/THz devices and antenna arrays.