IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received March 16, 2019, accepted March 25, 2019, date of publication April 11, 2019, date of current version April 19, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2908453

Compact Wide-Frequency Tunable Filter With Switchable Bandpass and Bandstop Frequency Response

KAIJUN SONG, (Senior Member, IEEE), WEIJIA CHEN, SHEMA RICHARD PATIENCE, YUXUAN CHEN, ABDELQANI MOHAMED IMAN, AND YONG FAN, (Senior Member, IEEE)

EHF Key Laboratory of Science, School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

Corresponding author: Kaijun Song (ksong@uestc.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61771094, and in part by the Sichuan Science and Technology Program under Grant 2019JDRC0008.

ABSTRACT In this paper, a novel compact wide-frequency tunable filter with switchable bandpass and bandstop frequency response is presented. By employing two PIN diodes between the source and load port, the bandpass and bandstop filtering response can be switched, respectively. Three varactor diodes have been used to tuning the operating frequency of the tunable filter at bandpass and bandstop frequency response. The even- and odd-mode method is applied to analyze the presented tunable filter. When PIN diode is forward-biased, the filter has the bandstop response, and the filter has bandpass response while it is reversed. To verify the proposed tunable filter circuits, the tunable bandpass filter and bandstop filter are designed, fabricated, and measured. It is demonstrated that the center frequency of the fabricated tunable filter is tuned from 0.95 to 1.35 GHz. The measured insertion loss in the band is greater than 13 and 11 dB for bandstop mode and bandpass mode, respectively. Moreover, the fabricated tunable filter has a compact size of $0.24\lambda_g \times 0.24\lambda_g$ (λ_g is the wavelength of the center frequency during the tunable frequency range).

INDEX TERMS Tunable filter, bandpass filter, bandstop filter, compact, PIN diode.

I. INTRODUCTION

Bandpass and bandstop filters are widely used in microwave and millimeter-wave circuits and systems due to the ability of selecting or suppressing signals at specific frequencies [1]–[12]. Over the past years, great attentions have been paid to tunable/reconfigurable filters based on various circuit structures, owning to their applications to reduce the complexity and strengthen expansibility in modern electronic systems [13]–[22]. The microstrip lines are often superior in many applications due to the compact structure and easy fabrication [13]. An inchoate tunable filter was proposed by Hunter and Rhodes in [14], where varactor diodes are loaded on the ends of comb-line bandpass filter, and wide frequency tuning ranges are achieved finally. Kim and Yun then improved this design by replacing the comb-lines with step-impedance lines to maintain a constant filter response shape and bandwidth in frequency tuning range [15]. A tunable bandpass filter was first presented with two independently adjustable transmission zeros by applying four varactor diodes loaded on different resonators in [16]. Chiou and Rebeiz proposed a tunable three-pole bandpass filter with bandwidth and transmission zero control in [17]. Two varactor diodes are employed among resonators so that the bandwidth is tunable.

The tunable bandpass filters are summarily categorized into three types in [18], which are fixed center frequency with tunable bandwidth, tunable center frequency with fixed bandwidth and tunable center frequency with tunable bandwidth, respectively. However, in some practical applications, it is desired to obtain a switching reconfigurable characteristic that the filter can work both on bandpass mode and bandstop mode [19]–[22]. In digital modulation, a reconfigurable filter with switchable bandpass and bandstop mode can be used easily to implement various modulation modes, such as Amplitude Shift Keying (ASK),

The associate editor coordinating the review of this manuscript and approving it for publication was Feng Lin.

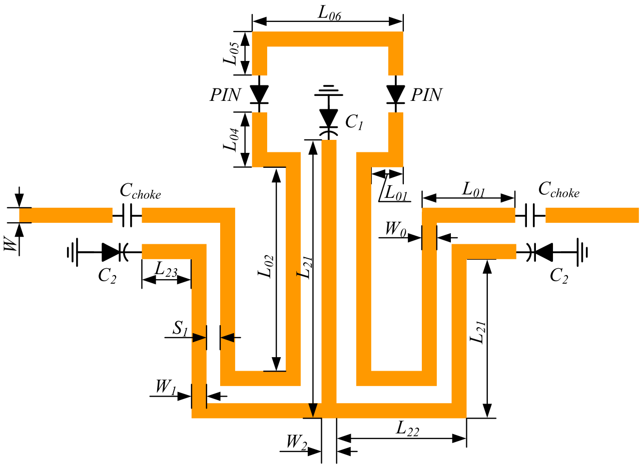

FIGURE 1. Schematic diagrams of proposed tunable filter.

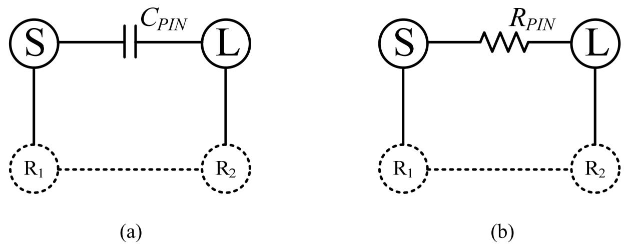

FIGURE 2. Coupling schematic topology (a) bandpass frequency response. (b) Bandstop frequency response.

Frequency Shift Keying (FSK) and Quadrature Phase Shift Keying (QPSK). Switchable operating mode is a very imperative feature of frequency tuning filters in different applications.

In this paper, a compact wide-frequency tunable filter with switchable bandpass and bandstop frequency response, as shown in Fig. 1, are proposed. By employing two PIN diodes and three varactor diodes, the bandpass and bandstop filtering response with tunable center frequencies from 0.95 to 1.35 GHz are achieved, respectively. At the same time, the even- and odd-mode analysis method and varactor's tuned characteristic formulas are introduced to provide the design procedure for the presented tunable filter simultaneously. Reasonable agreements between the simulated and measured results are achieved, which validates the validity of the design.

II. THEORY AND DESIGN EQUATIONS FOR FILTER

The proposed tunable filter is formed by five parts, such as E-type resonator, input and output microstrip feed lines, varactor diodes, PIN diodes, and bias circuits. Three varactor diodes are loaded on the ends of the resonator, and they constitute the tunable resonator unit with E-type microstrip resonator. The operating frequency of the tunable filter can be changed by tuning the voltages of the bias circuits for the three varactor diodes at bandpass or bandstop frequency response. The two PIN diodes are located on the ends of the input and output microstrip feed lines, respectively. Moreover, the other ends of the two PIN diodes are connected with a microstrip line, which can provide a RF signal transmission path when the tunable filter circuit is switched to bandstop filtering frequency response (in this case, the two PIN diodes are at the forward bias).

A. EQUIVALENT CIRCUITS AT DIFFERENT PIN BIAS STATE

According to Fig. 1, two PIN diodes between source and load ports are employed to realize switchable operating modes between the bandpass and bandstop frequency response. When the two PIN diodes are at the zero bias, they present large impedance owing to their very small junction capacitance (see Fig. 2(a)), and hence the tunable bandpass filtering frequency response is achieved in this case. This case corresponds to the tunable bandpass filter. To switch the tunable bandstop filter, a forward bias is applied to the two PIN diodes. At the forward bias, the PIN diode behaves like a very small resistance (see Fig. 2(b)) so that the input and output microstrip lines can be connected directly by the two PIN diodes and the microstrip line between the two PIN diodes, and thus RF signals can be transmitted directly from the input port to output port through the two PIN diodes and the microstrip line between the two PIN diodes. Moreover, the tunable bandstop frequency response will generate by using the parallel tunable E-type resonator loaded by three varactor diodes. As a consequence, the tunable bandstop filter is achieved. Then the bandpass and bandstop frequency response of the tunable filter can be switched by switching the state of the two PIN diodes. Fig. 2 illustrates the coupling structure of bandpass state and bandstop state for proposed filter, respectively, where dash line means the tunable part of the circuit and the solid line means it's fixed.

B. CAPACITANCE CHOICE FOR VARACTOR

The E-type resonator is equivalent to a center stub-loaded resonator loaded by three varactor diodes (each varactor diode can be simplified to a series capacitor attached on the ends of each port), as shown in Fig. 3(a). Due to its symmetry of the circuit structure, the even- and odd-mode method can be applied to analyze its characteristics. As it can be seen, under the even- or odd-mode excitations, the middle symmetric plane shown in Fig. 3(a) by short dash-line behaves as a perfect magnetic wall (M.W.) or electric wall (E.W.), respectively, and the bisection becomes a one-port network with open- and short- circuited end in M.W. and E.W. locations, respectively, as shown in Fig. 3(c) and Fig. 3(b). In even-mode equivalent circuit, the characteristic admittance (Y_2) of the center loaded stub and the end loaded equivalent capacitor (C_b) become one-half of the original ones. For convenience, it assumes that they have double value in original circuit, as shown in Fig. 3(a).

As shown in Fig. 3(b), the port admittance of P_1 in the odd-mode equivalent circuit is

$$Y_{odd} = j\omega C_a + jY_1 \cot\theta_1 \tag{1}$$

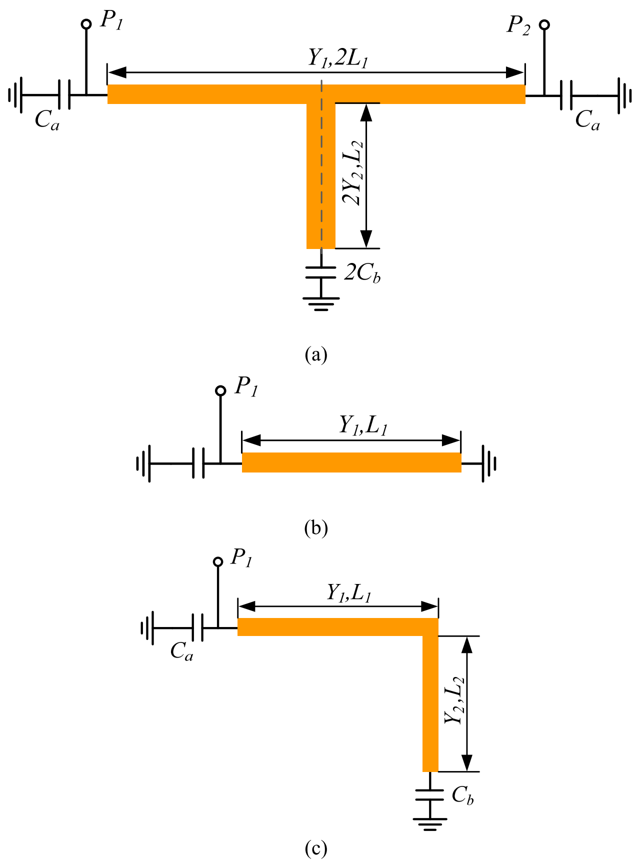

FIGURE 3. Equivalent circuit of E-type resonator loaded by three varactor diodes (a) Basic equivalent circuit. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit.

where θ_1 is the electrical length for the corresponding frequency ω and the length L_1 of the microstrip line. Its odd-mode resonant conditions can be expressed as

$$Y_{odd} = 0 \tag{2}$$

Hence, for the desired resonant odd-mode frequency, the value of the capacitor C_a can be derived as

$$C_a = \frac{Y_1 \cot\theta_{1o}}{\omega_o} \tag{3}$$

where θ_{1o} is the electrical length for resonant frequency ω_o. It can be seen that the odd-mode resonant frequency can be changed by Tuning C_a from (3).

Similarly, for the even-mode case, the even-mode equivalent circuit and the even-mode resonant conditions can also be obtained. In order to simplify derivation process, it assumes that the input admittance of the center loaded stub in even-mode circuit is Y_{2in}. Therefore, the port admittance of P_1 can be derived as

$$Y_{even} = j\omega C_a + Y_1 \frac{jY_1 \tan\theta_1 + Y_{2in}}{jY_{2in}\tan\theta_1 + Y_1} \tag{4}$$

where

$$Y_{2in} = jY_2 \frac{Y_2 \tan\theta_2 + \omega C_b}{-\omega C_b \tan\theta_2 + Y_2} \tag{5}$$

θ_2 is the electrical length for the corresponding frequency ω and the length L_2 of the microstrip line. Then, the even-mode resonant condition can also be express as

$$Y_{even} = 0 \tag{6}$$

Then,

$$j\omega_e C_a + Y_1 \frac{jY_1 \tan\theta_{1e} + Y_{2in}^{(e)}}{jY_{2in}^{(e)} \tan\theta_{1e} + Y_1} = 0 \tag{7}$$

where

$$Y_{2in}^{(e)} = jY_2 \frac{Y_2 \tan\theta_{2e} + \omega_e C_b}{-\omega_e C_b \tan\theta_{2e} + Y_2} \tag{8}$$

Substitute (8) to (7), the explicit formula for C_b with other parameters can be expressed as

$$C_b = \frac{Y_2^2 \tan\theta_{2e} + jY_{2in}^{(e)} Y_2}{j\omega_e Y_{2in}^{(e)} \tan\theta_{2e} - \omega_e Y_2} \tag{9}$$

where

$$Y_{2in}^{(e)} = jY_1 \frac{Y_1 \tan\theta_{1e} + \omega_e C_a}{\omega_e C_a \tan\theta_{1e} - Y_1} \tag{10}$$

ω_e is the even-mode resonate frequency, and θ_{1e} and θ_{2e} is the corresponding electrical length for microstrip L_1 and L_2. It is obvious that the even-mode resonant frequency is related with both C_a and C_b. If only one passband or stopband is needed for the tunable filter, ω_o and ω_e should be close to each other, and then, C_a and C_b should be trade-off.

To reveal this rule more obviously, let's define $\alpha = \omega_e/\omega_o$ denoting the multiplied relation between odd-mode and even-mode frequency. Thus α can be expressed as

$$\alpha = \frac{\omega_e}{\omega_o} = j\tan\theta_{1o} \frac{jY_1 \tan\theta_{1e} + Y_{2in}^{(e)}}{jY_{2in}^{(e)} \tan\theta_{1e} + Y_1} \tag{11}$$

Here, C_a is not included in this formula (11). Then, α is only depended on C_b. In other words, the frequency ω_o can be changed by C_a and the other frequency ω_e can be tuned by C_b. Then, the designing procedure of the presented tunable filter can be summarized as follows:

1) Fix the range of one side frequency ω_o by selecting a varactor diode (can be simplified to the capacitor C_a) with a proper tunable frequency range.

2) Tune the capacitor C_a and let the passband and stopband in the tunable frequency range.

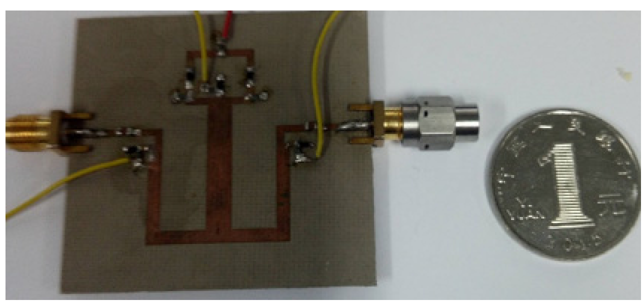

FIGURE 4. Photograph of the fabricated tunable filter.

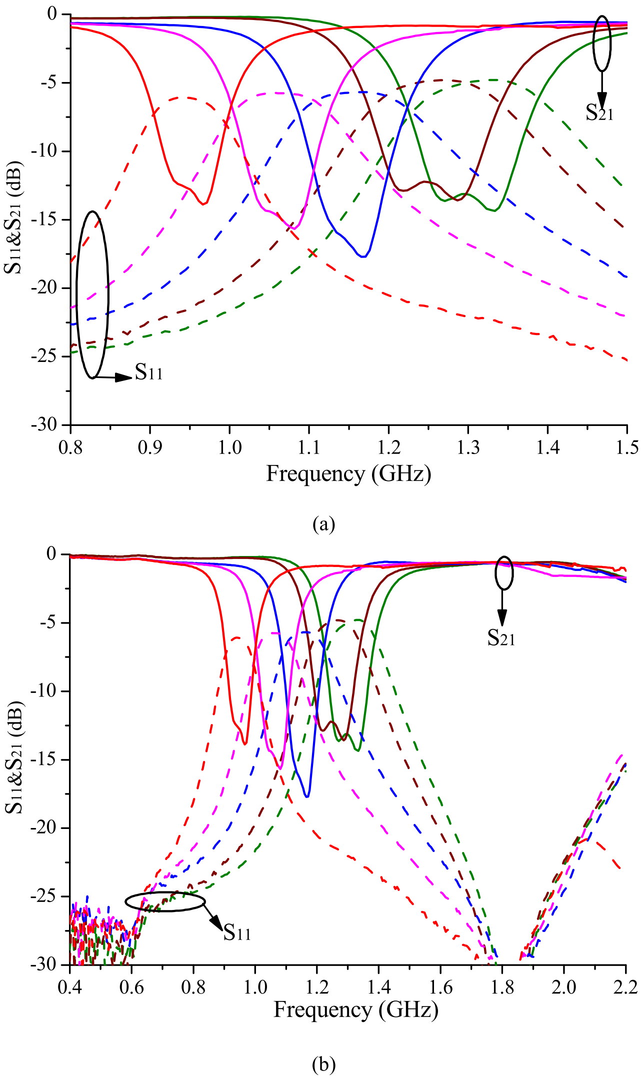

FIGURE 5. Measured results of the fabricated tunable filter with bandpass frequency response: (a) In-band. (b) Wideband.

3) Select another proper varactor diode (can be simplified to the capacitor C_b), and design the circuit coupling between the input/output feedlines and resonator by adjusting the width of the coupling slot S_1.

III. EXPERIMENTAL RESULTS

According to the above analysis and design method, the presented tunable filter is designed and fabricated on Taconic RF-35(tm) substrate with a thickness of 0.508 mm, relative dielective constant of 3.5 and loss tangent of 0.0018. In addition, the isolation between DC and RF signals is gotten by applying RF choke and bypass capacitor for DC bias circuit of the two PIN diodes and three varactor diodes. Varactor diodes C_1 (SMV-1232-079LF) and C_2 (SMV-1231-079LF) are from SKYWORKSS(tm) Inc, and the tunable ranges of them are 0.466-2.35 pF and 0.72-4.15 pF, respectively. The two PIN diodes (SMP-1230-079LF) are also from SKYWORKSS(tm) Inc. The photograph of the fabricated tunable filter with switchable bandpass and bandstop frequency response is shown in Fig.4, and its total size is 42 mm × 35 mm. The final dimensions are listed in Table 1.

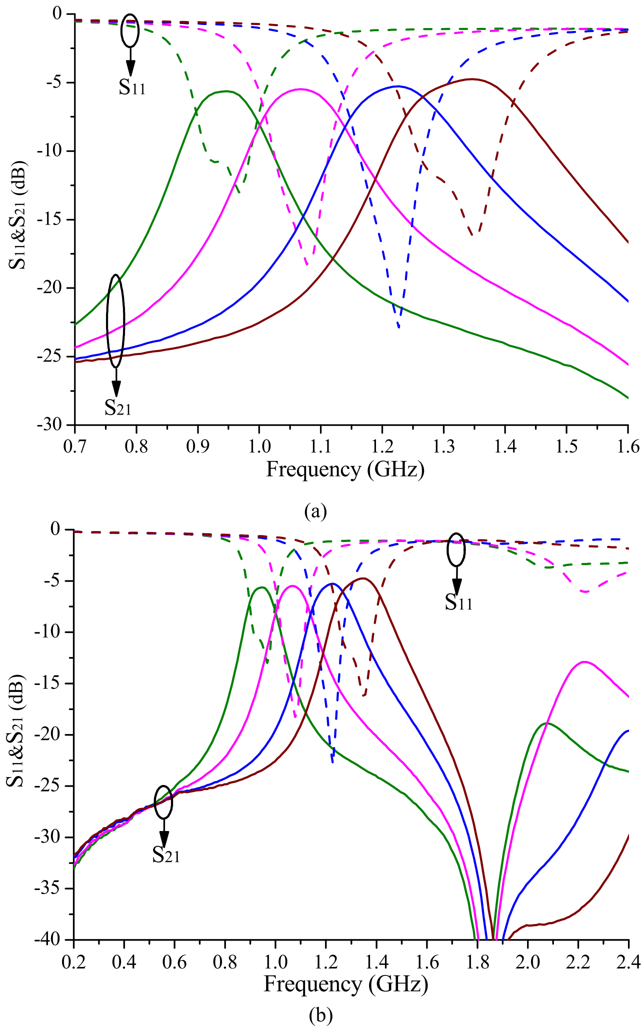

FIGURE 6. Measured results of the fabricated tunable filter with bandpass frequency response: (a) In-band. (b) Wideband.

TABLE 1. Circuit dimensions of the tunable filter.

W	1.14	L_{02}	20.7	L_1	25.82
W_0	1.2	L_{03}	3.7	L_{21}	10
W_1	1.43	L_{04}	4.2	L_{22}	15.2
W_2	0.82	L_{05}	4.2	L_{23}	1.5
L_{01}	5.8	L_{06}	11.13	All units are in mm	

Fig.5 shows the measured results of the fabricated tunable filter with bandstop frequency response when the two PIN diodes are at the forward bias. Measured attenuation within the stopband is greater than 13 dB with the rejection FBW of 3% to 7%, while the measured insertion loss is less than 0.5 dB within the low passband and less than 1 dB in the upper passband up to 2.2 GHz. In addition, the measured return loss is about 20 dB within the low passband and the upper passband. For the bandstop mode, the tunable center frequency range of the stopband is from 0.95 to 1.35 GHz by tuning the biased voltage of the three varactor diodes.

The measured results of the fabricated tunable filter with bandpass frequency response are shown in Fig. 6. In this case, the two PIN diodes are at the zero bias. The measured return loss is greater than 11 dB within the passband, while the measured insertion loss is between 4.7 and 5.6 dB with the 3-dB FBW of greater than 15%. The measured out-of-band attenuation is greater than 25dB within the low stopband and upper stopband. The tunable center frequency range of the passband for the fabricated tunable filter is also from 0.95 to 1.35 GHz.

IV. CONCLUSION

A compact PIN-based tunable filer has been presented and developed. The bandpass and bandstop frequency response of the presented tunable filter can be switched when the center frequency has been tuned. The equivalent circuit of the presented tunable filter is analyzed by employing even- and odd-mode analysis theory. The presented tunable bandpass and bandstop filter is designed and fabricated to verify the proposed analysis and design method. The fabricated tunable filter demonstrates a wide frequency tuning range with a miniaturized circuit size of 0.14λg × 0.12λg. It can be seen that the designed tunable filter has the advantages of switchable bandpass and bandstop frequency response, wide frequency tuning range, simple circuit, and compact size, which make it very competitive in the practical system applications.

REFERENCES

[1] J. J. Sánchez-Martínez, M. Pérez-Escribano, and E. Márquez-Segura, "Synthesis of dual-band bandpass filters with short-circuited multiconductor transmission lines and shunt open stubs," *IEEE Access*, vol. 7, pp. 24071–24081, Feb. 2019.

[2] E.-W. Chang and Y.-S. Lin, "Miniature multi-band absorptive bandstop filter designs using bridged-T coils," *IEEE Access*, vol. 6, pp. 73637–73646, Nov. 2018.

[3] S. Soeung, S. Cheab, and P. W. Wong, "Lossy asymmetrical bandstop filter based on a multiple triplet realization," *IEEE Access*, vol. 6, pp. 1284–1291, Nov. 2017.

[4] Y. Wu, L. Cui, W. Zhang, L. Jiao, Z. Zhuang, and Y. Liu, "High performance single-ended wideband and balanced bandpass filters loaded with stepped-impedance stubs," *IEEE Access*, vol. 5, pp. 5972–5981, 2017.

[5] K. Song and Q. Xue, "Inductance-loaded Y-shaped resonators and their applications to filters," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 4, pp. 978–984, Apr. 2010.

[6] D. Bukuru, K. Song, F. Zhang, Y. Zhu, and M. Fan, "Compact quad-band bandpass filter using quad-mode stepped impedance resonator and multiple coupling circuits," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 3, pp. 783–791, Mar. 2017.

[7] F. Chen, K. Song, B. Hu, and Y. Fan, "Compact dual-band bandpass filter using HMSIW resonator and slot perturbation," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 10, pp. 686–688, Oct. 2014.

[8] Y. Mo, K. Song, and Y. Fan, "Miniaturized triple-band bandpass filter using coupled lines and grounded stepped impedance resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 5, pp. 333–335, May 2014.

[9] K. Song and Q. Xue, "Compact ultra-wideband (UWB) bandpass filters with multiple notched bands," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 8, pp. 447–449, Aug. 2010.

[10] W.-H. Tu and K. Chang, "Compact microstrip bandstop filter using open stub and spurline," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 4, pp. 268–270, Apr. 2005.

[11] A. Ebrahimi, W. Withayachumnankul, S. F. Al-Sarawi, and D. Abbott, "Compact second-order bandstop filter based on dual-mode complementary split-ring resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 8, pp. 571–573, Aug. 2016.

[12] J. Hinojosa, M. Rossi, A. Saura-Ródenas, A. Álvarez-Melcón, and F. L. Martínez-Viviente, "Compact bandstop half-mode substrate integrated waveguide filter based on a broadside-coupled open split-ring resonator," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 3001–3010, Jun. 2018.

[13] P. Wong and I. Hunter, "Electronically tunable filters," *IEEE Microw. Mag.*, vol. 10, no. 1, pp. 46–54, Jan. 2009.

[14] I. C. Hunter and J. D. Rhodes, "Electronically tunable microwave bandpass filters," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-30, no. 9, pp. 1354–1360, Sep. 1982.

[15] B.-W. Kim and S.-W. Yun, "Varactor-tuned combline bandpass filter using step-impedance microstrip lines," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 4, pp. 1279–1283, Apr. 2004.

[16] J. Long, C. Li, W. Cui, J. Huangfu, and L. Ran, "A tunable microstrip bandpass filter with two independently adjustable transmission zeros," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 2, pp. 74–76, Feb. 2011.

[17] Y. Chiou and G. M. Rebeiz, "A tunable three-pole 1.5-2.2-GHz bandpass filter with bandwidth and transmission zero control," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 11, pp. 2872–2878, Nov. 2011.

[18] H.-J. Tsai, B.-C. Huang, N.-W. Chen, and S.-K. Jeng, "A reconfigurable bandpass filter based on a varactor-perturbed, T-shaped dual-mode resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 5, pp. 297–299, May 2014.

[19] M. F. Karim, A. Q. Liu, A. Alphones, and A. B. Yu, "A novel reconfigurable filter using periodic structures," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2006, pp. 943–946.

[20] Y.-M. Chen, S.-F. Chang, C.-Y. Chou, and K.-H. Liu, "A reconfigurable bandpass-bandstop filter based on varactor-loaded closed-ring resonators," *IEEE Microw. Mag.*, vol. 10, no. 1, pp. 138–140, Feb. 2009.

[21] E. J. Naglich, J. Lee, D. Peroulis, and W. J. Chappell, "A tunable bandpass-to-bandstop reconfigurable filter with independent bandwidths and tunable response shape," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3770–3779, Dec. 2010.

[22] J. Lee, E. J. Naglich, H. H. Sigmarsson, D. Peroulis, and W. J. Chappell, "New bandstop filter circuit topology and its application to design of a bandstop-to-bandpass switchable filter," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 3, pp. 1114–1123, Mar. 2013.

KAIJUN SONG (M'09–SM'12) received the M.S. degree in radio physics and the Ph.D. degree in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2005 and 2007, respectively.

He was a Full Professor with UESTC, where he has been with the EHF Key Laboratory of Science, School of Electronic Engineering, since 2007. Since 2018, he has been a Full Professor with the School of Electronic Science and Engineering, UESTC. From 2007 to 2008, he was a Postdoctoral Research Fellow of Montana Tech, University of Montana, Butte, USA, where he was involved in microwave/millimeter-wave circuits and microwave remote sensing technologies. From 2008 to 2010, he was a Research Fellow of the State Key Laboratory of Millimeter Waves, Department of Electronic Engineering, City University of Hong Kong, China, where he was involved in microwave/millimeter-wave power-combining technology and ultra-wideband (UWB) circuits. He was a Senior Visiting Scholar with the State Key Laboratory of Millimeter Waves, Department of Electronic Engineering, City University of Hong Kong, China, in 2012. He has published over 200 internationally refereed journal papers and conference papers. His current research interests include microwave and millimeter-wave/THz power-combining technologies, high-power solid-state microwave/millimetre-wave technologies, UWB circuits and technologies, and microwave/millimetre-wave devices, circuits, and systems. He is a Reviewer of 10s of international journals, including the IEEE Transactions and the IEEE Letters. In 2011, he has received the New Century Excellent Talents in University Award from the Chinese Ministry of Education. In 2015, he has received the academic and technical leaders in Sichuan. In 2019, he has received the Scientific and Technological Innovation Talents in Sichuan.

WEIJIA CHEN was born in Hunan, China, in 1996. He received the B.S. degree from the Hefei University of Technology, Hefei, China, in 2018. He is currently pursuing the M.S. degree with the University of Electronic Science and Technology of China (UESTC), Chengdu, China. He is interested in microwave technologies.

SHEMA RICHARD PATIENCE was born in Kigali, Rwanda, in 1988. He received the B.S. degree in electrical and electronic engineering from the National University of Rwanda, Huye, Rwanda, in 2012, and the M.Eng. degree in electronic science and technology from the Beijing Institute of Technology, Beijing, China, in 2015. He joined the University of Electronic Science and Technology of China (UESTC), in 2017, where he is currently pursuing the Ph.D. degree. His research interests include microwave/millimeter wave substrate integrated waveguide power dividers/combiners and passive components design in RF circuits.

YUXUAN CHEN was born in Nanchang, Jiangxi, China, in 1996. She received the B.S. degree in engineering from Southwest University, Chongqing, China, in 2018. She is currently pursuing the M.S. degree in electronics and communication engineering with the University of Electronic Science and Technology of China. Her research interests include millimetre-wave and terahertz wave power-combining technology.

ABDELQANI MOHAMED IMAN received the B.S. degree in mechanical and electronic engineering from the Shandong University of Science and Technology, in 2016, and the M.S. degree in electronic engineering from the University of Electronic Science and Technology of China, in 2018, where he is currently pursuing the Ph.D. degree in electronic engineering. His current research interests include microwave high power combining technologies.

YONG FAN (M'05–SM'18) received the B.E. degree from the Nanjing University of Science and Technology, Nanjing, Jiangsu, China, in 1985, and the M.S. degree from the University of Electronic Science and Technology of China, Chengdu, Sichuan, China, in 1992.

From 1985 to 1989, he was interested in microwave integrated circuits. He has authored or coauthored over 100 papers, 80 of which are searched by SCI and EI. Since 1989, he has been involved in millimeter-wave communication, electromagnetic theory, millimeter-wave technology, and millimeter-wave systems. He is currently a Senior Member of Chinese Institute of Electronics.