Received: 7 August 2019 | Revised: 18 December 2019 | Accepted: 4 February 2020
DOI: 10.1002/mmce.22193

RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF RF AND MICROWAVE COMPUTER-AIDED ENGINEERING WILEY

Wideband bandpass filtering branch-line balun with high-isolation

Phirun Kim | **Yongchae Jeong**

Division of Electronics and Information Engineering, IT Convergence Research Center, Jeonbuk National University, Jeonju, Republic of Korea

Correspondence
Yongchae Jeong, Division of Electronics and Information Engineering, IT Convergence Research Center, Jeonbuk National University, Jeonju, Republic of Korea.
Email: ycjeong@jbnu.ac.kr

Funding information
NRF, Grant/Award Number: 2019R1A6A1A09031717

Abstract
The wideband bandpass filtering branch-line balun with high isolation is presented in this paper. The proposed balun can be designed for wideband performances by choosing a proper characteristics impedance of input vertical transmission line and odd-mode impedance of parallel-coupled lines. The proposed balun was designed at a center frequency (f_0) of 3.5 GHz for validation. The measured results are in good agreement with the simulations. The measured power divisions are -3.31 dB and -3.24 dB at f_0 and -3 ± 0.17 dB within the bandwidth of 0.95 GHz (3 GHz to 3.95 GHz). The input return loss of 24.09 is measured at f_0 and higher than 20 dB over the same bandwidth. Moreover, the measured output losses are better than 11 dB within a wide bandwidth. The isolation between output ports is 20.32 dB at f_0 and higher than 13.2 dB for a broad bandwidth from 1 GHz to 10 GHz. The phase difference and magnitude imbalance between two output ports are $180^\circ \pm 4.5^\circ$ and ± 0.95 dB, respectively, for the bandwidth of 0.95 GHz.

KEYWORDS
bandpass filtering, branch-line balun, coupled line, isolation circuit, wideband

1 | INTRODUCTION

A branch-line balun is an important three-port device that can divide input signal into two output signals with equal power and out-of-phase. Since, the balun has been used for various applications such as amplifiers, antennas, and mixers, the high isolation between output ports and bandpass filtering are the important design issues. Although, the marchand,[1] branch line,[2] dual-mode balun,[3,4] slot-line resonator,[5] and ring resonator[6] had been designed and provided a good passband response, the stopband performance and/or isolation characteristics were limited.

In Reference 7, a branch-line baluns with open circuit stub transmission lines (TLs) on its vertical branches was designed to suppress an unwanted even-mode signal and could reduce the total circuit size. However, the electrical performances had relatively narrow bandwidth and did not consider the isolation between output ports. On the other hand, 3 dB Marchand balun and branch-line balun with a new isolation circuit had showed a good passband performance and high isolation, but stopband characteristic was poor.[8,9] A bandpass filtering dual-mode balun with quarter-wavelength (λ/4) stepped impedance resonator (SIR) was proposed in Reference 10. Although, the bandpass filtering with a narrow bandwidth and controllable spurious response could be obtained, the isolation performance was not considered.

In this paper, a wideband bandpass filtering branch-line balun is proposed with high isolation characteristics using two TLs and two parallel-coupled lines. In addition, the proposed balun can be designed for narrow band or wideband by choosing the proper input vertical TLs and odd-mode impedance of coupled lines impedance.

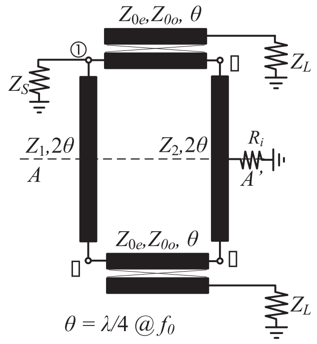


FIGURE 1 Block diagram of proposed unequal termination branch-line balun

2 | ANALYSIS

Figure 1 shows the proposed circuit of the bandpass filtering branch-line balun with high isolation circuit. The proposed circuit consists of two open-circuited coupled lines with electrical length of λ/4, two TLs with electrical length of λ/2, and isolation resistance R_i. The R_i is connected at the center of the output port of vertical TL for the high isolation purpose. The proposed balun is analyzed from the symmetrical four-port network where one of the ports is terminated as an open.[9]

From Reference [11], the even- and odd-mode excitations can be used to analyze the proposed circuit. Figures 2A,B show the even- and odd-mode equivalent circuits, respectively. For balun operation, transmission stop ($T_{even} = 0$) condition has to be presented in the even-mode equivalent circuit. On the other hand, sum of the even- and odd-mode input impedances must be twice the source impedance ($Z_{even} + Z_{odd} = 2Z_S$). Under the even-mode excitation, the open stubs TLs with electrical length of λ/4 at f_0 is transformed to short-circuited ($Z_{even} = 0$) at the junction point 1. Thus, $T_{even} = 0$ can be obtained at f_0. Under the odd-mode excitation, the symmetry plan AA' become short circuit and R_i does not have any effect on the circuit operation. The odd-mode reflection and transmission coefficients are derived as (1) from the ABCD-parameters.

$$S_{11o} = \frac{A_o Z_L + B_o - C_o r Z_L^2 - D_o r Z_L}{A_o Z_L + B_o + C_o r Z_L^2 + D_o r Z_L} \tag{1a}$$

$$S_{21o} = \frac{2Z_L\sqrt{r}}{A_o Z_L + B_o + C_o r Z_L^2 + D_o r Z_L}, \tag{1b}$$

where

$$A_o = \frac{Z_p\left(2Z_2 + Z_p\right)}{2Z_2 Z_m \csc\theta \tan\theta} \tag{2a}$$

$$B_o = j\frac{x_1^2 - x_2}{2x_1\left(2Z_2 \tan^2\theta - Z_p\right)} \tag{2b}$$

$$C_o = j\frac{2x_3 - Z_{p1}\left(2Z_1 + 2Z_2 + Z_p\right)}{x_3 Z_m \csc\theta} \tag{2c}$$

$$D_o = \frac{x_1^2 - x_2}{2x_1 Z_1 \tan\theta\left(2Z_2 \tan^2\theta - Z_p\right)} + \frac{2Z_2 Z_p \tan^2\theta + Z_m^2 - Z_p^2}{x_1 \tan\theta} \tag{2d}$$

$$x_1 = 2Z_m Z_2 \csc\theta \tan^2\theta \tag{2e}$$

$$x_2 = \left(Z_m^2 + 2Z_2 Z_p \tan^2\theta - Z_p^2\right)\left(Z_p^2 + 2Z_2 Z_p\right) \tag{2f}$$

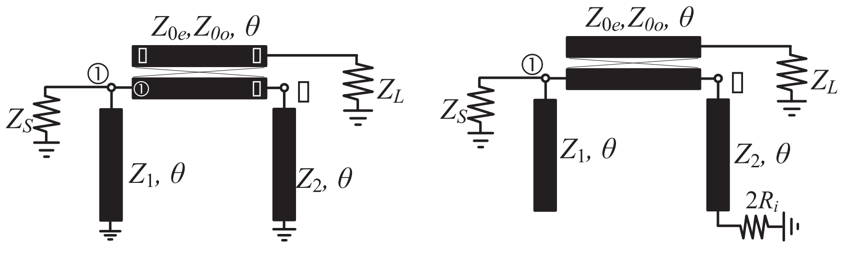
$$x_3 = 2Z_1 Z_2 \tan^2\theta \tag{2g}$$

$$r = Z_S/Z_L \tag{2h}$$

At a center frequency (f_0), the even-mode impedance (Z_{0e}) of parallel coupled lines can be derived from (1a) as a function of odd-mode impedance (Z_{0o}) of parallel coupled line as (3).

$$Z_{0e} = 2Z_L\sqrt{r} + Z_{0o}, \tag{3}$$

where Z_{0o} can be chosen arbitrarily.



(A) (B)

FIGURE 2 Equivalent circuit of proposed structure: A, Odd-mode and, B, even-mode excitations

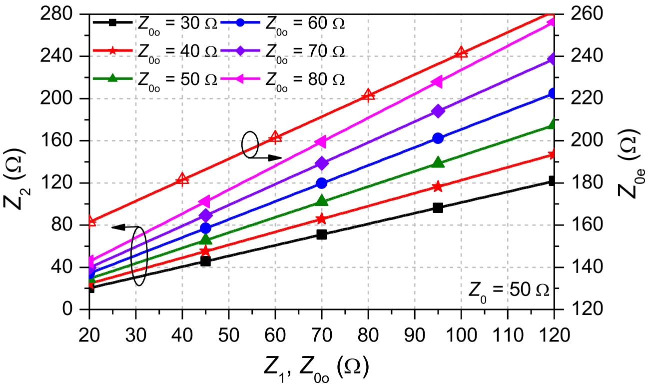


FIGURE 3 Variation of Z_2 and Z_{0e} according to Z_1 and Z_{0o}

Similarly, the characteristic impedance of Z_2 can be derived as (4).

$$Z_2 = \frac{Z_1 Z_p^2}{Z_1 Z_p (r-2) + r Z_m^2}, \tag{4}$$

where

$$Z_p = Z_{0e} + Z_{0o} \tag{5a}$$

$$Z_m = Z_{0e} - Z_{0o}. \tag{5b}$$

And the characteristic impedance Z_1 can be also chosen arbitrarily within the realizable fabrication range. Figure 3 shows the variations of Z_2 and Z_{0e} according to Z_1 and Z_{0o}, respectively. Z_{0e} is increased as Z_{0o} increases. Similarly, Z_2 is increased as Z_1 and Z_{0o} increase. In practical, Z_2 can be designed within the realizable fabrication range of 20 Ω to 130 Ω in typical microstrip line technology, so Z_1 and Z_{0o} should be selected properly.

The high isolation can be obtained by isolation resistance (R_i). The R_i can be derived from the odd- and even-mode equivalent circuits of proposed balun. From the odd-mode equivalent circuit, S_{22o} at f_0 can be simplified as (6).

$$S_{22o}\big|_{f=f_0} = \frac{Z_m^2 - 4rZ_L^2}{Z_m^2 + 4rZ_L^2} \tag{6}$$

For the even-mode excitation, the R_i is split into half along the axis-AA' and its resistance is doubled, as shown in Figure 2B. S_{22e} at f_0 can be obtained as (7).

$$S_{22e}\big|_{f=f_0} = \frac{Z_2^2 Z_m^2 - Z_p^2 Z_L^2 2R_i}{Z_2^2 Z_m^2 + Z_p^2 Z_L^2 2R_i} \tag{7}$$

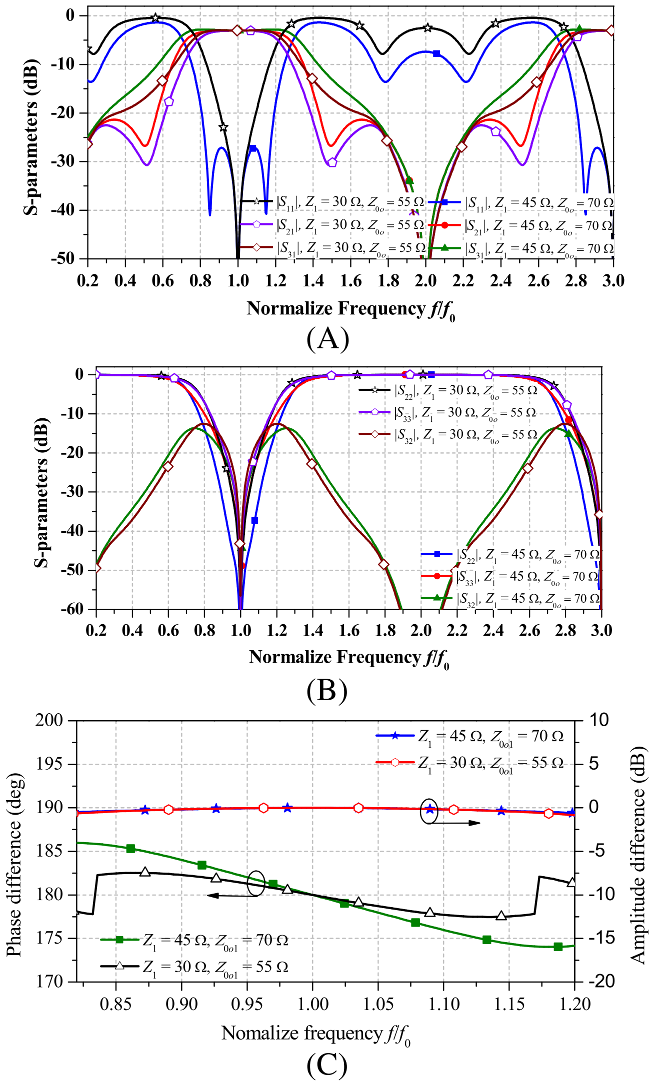


FIGURE 4 Bandpass filtering branch line balun characteristics: A, S-parameters, B, output return loss and isolation, and C, phase difference and magnitude imbalance

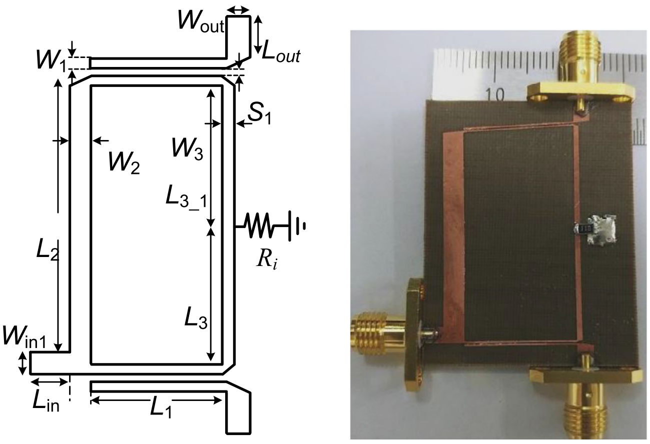
Then S_{32} of balun at f_0 can be obtained from (6) and (7).[12]

$$S_{32}\big|_{f=f_0} = \frac{S_{22e}\big|_{f=f_0} - S_{22o}\big|_{f=f_0}}{2} \tag{8}$$

By setting (8) to zero, a high isolation can be obtained at the f_0. Additionally, R_i can be derived as (9).

$$R_i = \frac{2Z_2^2 r Z_L}{Z_p^2} \tag{9}$$

To illustrate the design equations, the balun were designed for both narrow band and wideband responses. The Z_1 = 30 Ω and Z_{0o} = 55 Ω are chosen for narrow band



(A) (B)

FIGURE 5 Proposed balun: A, Layout and B, photograph of fabricated PCB

TABLE 1 Physical dimensions and component value of fabricated PCB (unit: mm)

$W_{in} = W_{out} = 2.4$	$L_1 = 16$	$L_2 = 30.9$	$W_3 = 0.8$
$L_{in} = L_{out} = 3$	$S_1 = 0.18$	$L_3 = L_{3\_1} = 15.75$	
$W_1 = 0.25$	$W_2 = 3$	$R_i = 11\ \Omega$	

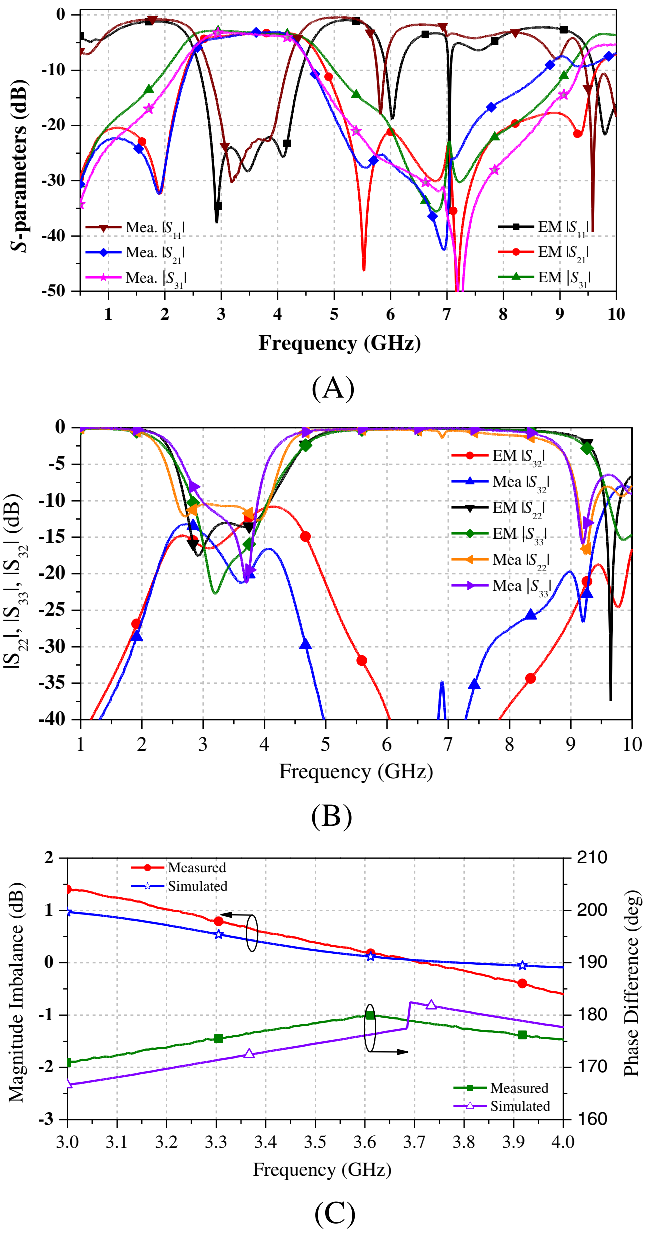


FIGURE 6 Simulation and measurement results of proposed balun: A, S-parameters, B, output return losses and Isolation, and, C, phase difference and magnitude imbalance

characteristics. Then, $Z_2 = 47.41\ \Omega$ and $Z_{0e} = 196.42\ \Omega$ are calculated using (3) and (4), respectively. Moreover, the $R_i = 7.11\ \Omega$ is calculated from (9). On the other hand, $Z_1 = 45\ \Omega$ and $Z_{0o} = 70\ \Omega$ are chosen for wideband characteristics. From (3), (4), and (9), $Z_2 = 89.09\ \Omega$, $Z_{0e} = 211.42\ \Omega$, and $R_i = 20.05\ \Omega$ are calculated, respectively. Figure 4 shows the insertion loss, input/output return losses, isolation, magnitude imbalance, and phase difference of the proposed balun with narrow and wideband responses. The S_{21} and S_{31} characteristics are almost same within the passband as shown in Figure 4A. The wide passband with three transmission poles (TPs) can be obtained by choosing proper Z_1 and Z_{0o}. Moreover, the stopband of S_{21} is attenuated by transmission zeros (TZs) that produce by the open/short stub TLs. The bandwidth of 26 dB return loss is extended from $0.828f_0$ to $1.173f_0$ with factional bandwidth (FBW) of 34.5%. A TP is obtained in the passband in condition of narrow band with 26 dB return loss FBW of 12% ($0.94\ f_0$ to $1.06\ f_0$). Figure 4B shows the output return losses and isolation characteristics. Good output return losses and isolation characteristics are obtained at f_0. Figure 4C shows the phase difference and magnitude imbalance between the output ports. The phase differences of 180° are obtained at f_0. Moreover, the phase differences better than $180° \pm 2.5°$ are obtained within FBW of 34.5% and 12%, respectively. On the other hand, the magnitude imbalance of both baluns is almost 0 dB within FBW of 34.5%. The bandwidth of proposed balun can be extended, but the fabrication of parallel-coupled line can be difficult with conventional microstrip technology. Thus, a tradeoff between realization and electrical performances has to be considered.

3 | SIMULATION AND MEASUREMENT RESULTS

To demonstrate and validate the analysis, the branch-line wideband balun was designed at $f_o = 3.5$ GHz. The circuit

TABLE 2 Performances comparison with previous works

	This work	1	2	3	4	5	
f_0 (GHz)	3.5	1	2.4	2	1	1.5	2.6
BP response	Yes	NA	NA	Yes	NA	NA	NA
FBW (%)	27.14*	82**	≈8.3**	11 (3 dB)	15*	20**	20 (−19 dB)
Phase diff.	±4.5°	±1°	±0.5°	±2.5°	±5°	±2°	±5°
Amp. im. (dB)	±0.95	±0.1	NA	±0.18	NA	NA	NA
Isolation (dB)	20.32	NA	NA	NA	NA	20 at f_0	19
Circuit size (mm^2)	35 × 25	40 × 64.5	NA	40.2 × 29	NA	NA	35 × 55

Abbreviation: Im., imbalance.

*−20 dB S_{11} FBW.

**−10 dB S_{11} FBW.

was fabricated on Taconic TLY substrate with $\varepsilon_r = 2.2$ and $h = 31$ mils. EM simulation was performed using ANSYS HFSS 2019R1. Figure 5 shows the EM simulation layout and a photograph of the fabricated balun. The physical dimensions and component value are shown in Table 1. The overall circuit size of fabricated balun is 35 mm × 25 mm.

Figure 6 shows the simulation and measurement results of the proposed balun. The measured results are consistence with the simulations. Figure 6A shows the measured S_{21}, S_{31}, and S_{11} are −3.31 dB, −3.24 dB, and $-$ 24.09 dB at f_0, respectively. The measured 20 dB return loss of the passband bandwidth is 0.95 GHz (3 to 3.95 GHz). The magnitude division of -3 ± 0.17 dB is obtained within the same bandwidth. Moreover, the output return losses are better than 11 dB in the passband as shown in Figure 6B. The isolation between the output ports is obtained 20.32 dB at f_0 and higher than 13.2 dB over a broad bandwidth from 1 GHz to 10 GHz as shown in Figure 6C. The tolerance of R_i and parasitics of TLs and parallel-coupled line can deteriorate the isolation and output return loss performances. The measured phase difference between two output ports is $180^\circ \pm 4.5^\circ$ over the passband. Moreover, the magnitude imbalance is less than ±0.95 dB within the same bandwidth.

The performances comparison is summarized in Table 2. The proposed balun is more advantageous and provides wideband, high isolation characteristics, and bandpass filtering response simultaneously.

4 | CONCLUSION

In this paper, a bandpass filtering branch-line balun with high isolation is presented. The proposed circuit employs two open-circuited coupled lines, two transmission lines and isolation resistance R_i. The design equations of proposed balun have been derived and validated with simulations and measurements. The bandwidth of proposed balun can be controlled for narrow or wide band by changing the characteristic impedance of the input vertical transmission line and odd-mode impedance of coupled line. The measurement and simulation are in good agreement. The proposed balun is expected to design for the wide and narrow bands with high isolation and bandpass filtering response. As the future work, the bandpass filtering balun with wide stopband is going on by using the coupling topology.

ACKNOWLEDGEMENT

This work was supported by Basic Science Research Program through NRF funded by Ministry of Education under Grant Number: 2019R1A6A1A09031717.

ORCID

Phirun Kim https://orcid.org/0000-0002-3889-8253
Yongchae Jeong https://orcid.org/0000-0001-8778-5776

REFERENCES

1. Zhang Z, Guo Y, Ong L, Chia M. Improved planar marchand balun using a patterned ground plane. *Int J RF Microw Comput-Aid Eng*. 2005;15(3):307-316.
2. Leong Y, Ang K, Lee C. A derivation of a class of 3-port baluns from symmetrical 4-port networks. *IEEE MTT-S International Microwave Symposium Digest*. Seattle, WA: IEEE; 2002:1165-1168.
3. Wang J, Huang F, Zhu L, Cai C, Wu W. Study of a new planar-type balun topology for application in the design of balun bandpass filters. *IEEE Trans Microw Theory Tech*. 2016;64(9):2824-2832.
4. Sun S, Menzel W. Novel dual-mode balun bandpass filters using single cross-slotted patch resonator. *IEEE Microw Wireless Compon Lett*. 2011;21(8):415-417.
5. Feng L-P, Zhu L. Wideband balun filter on slot-line resonator with intrinsic balanced performance in magnitude and phase. *Int J RF Microw Comput Aided Eng*. 2019;29:e21605.

6. Kang S-J, Hwang H-Y. Ring-balun-bandpass filter with harmonic suppression. *IET Microw Anten Propag*. 2010;4(11):1847-1854.
7. Park M-J, Lee B. Stubbed branch-line balun. *IEEE Microw Wireless Compon Lett*. 2007;17(3):169-171.
8. Ahn H-R, Nam S. New design formulas for impedance-transforming 3-dB Marchand baluns. *IEEE Trans Microw Theory Tech*. 2011;59(11):2816-2823.
9. Kim P, Chaudhary G, Jeong Y. Unequal termination branch-line balun with high-isolation wideband characteristics. *Micro Optic Techno Lett*. 2016;58(8):1775-1778.
10. Kim P, Chaudhary G, Jeong Y. A design of balun bandpass filter for wide stopband attenuation base on stepped impedance resonators. *Asia-Pacific Microwave Conference (APMC)*. Kyoto, Japan: IEEE; 2018:1339-1341.
11. Ang K-S, Leong Y-C, Lee C-H. Analysis and design of miniaturized lumped-distributed impedance-transforming baluns. *IEEE Trans. Microw Theory Tech.* 2003;51(3):1009-1017.
12. Hong J-S. *Microstrip Filter for RF/Microwave Applications*. 2nd ed. John Wiley & Sons; 2011 Chapter 2.

AUTHOR BIOGRAPHIES

Phirun Kim received his BE degree in electronics engineering from the National Polytechnic Institute of Cambodia (NPIC), Phnom Penh, Cambodia, in 2010, and his ME and PhD degrees in electronics engineering from Jeonbuk National University, Jeonju, Republic of Korea, in 2013 and 2017, respectively. He is currently a contract professor at HOPE-IT Human Resource Development Center-BK21 PLUS, Division of Electronics Engineering, Jeonbuk National University. He has authored and co-authored over 50 papers in international journals and conference proceedings. His research interests include planar passive filters, power dividers, impedance transformers, baluns, and high-efficiency power amplifiers.

Yongchae Jeong received the BSEE, MSEE, and PhD degrees in electronics engineering from Sogang University, Seoul, Korea, in 1989, 1991, and 1996, respectively. From 1991 to 1998, he was a Senior Engineer with Samsung Electronics. From 1998, he joined the Division of Electronics Engineering, Jeonbuk National University, Jollabuk-do, Korea. From July 2006 to December 2007, he was with the Georgia Institute of Technology, as a Visiting Professor. He is currently a Professor and member of the Information Technology (IT) Convergence Research Center, and Director of the HOPE-IT Human Resource Development Center, BK21 PLUS, Jeonbuk National University. He currently teaches and conducts research in the area of microwave passive and active circuits, mobile and satellite base-station RF systems, design of periodic defected transmission lines, and RF integrated circuit (RFIC) design. He has authored or coauthored over 250 papers in international journals and conference proceedings. Dr. Jeong is a member of the Korea Institute of Electromagnetic Engineering and Science (KIEES).

How to cite this article: Kim P, Jeong Y. Wideband bandpass filtering branch-line balun with high-isolation. *Int J RF Microw Comput Aided Eng*. 2020;30:e22193. https://doi.org/10.1002/mmce.22193