LETTER

Design of a 35–95 GHz fundamental monolithic mixer based on a novel IF extraction structure

Zhen Lin^{1,3}, Shengzhou Zhang^{2,3}, Dinghong Jia^{2,3}, Xiaolin Liang^{2,3}, Jianqin Deng^{2,3}, and Fushun Nian^{2,3a)}

Abstract The letter presents a high-performance doubly balanced ring mixer (DBRM) fabricated by a 0.1 μm GaAs pHEMT process that achieves ultrawide radio-frequency (RF) and intermediate frequency (IF) bandwidths. A multiple-coupled-line Marchand balun is optimized to extend the RF bandwidth. A novel structure is designed to directly extract the IF current from the RF balun without an additional IF coupler. Due to the proposed IF extraction structure, the IF bandwidth is broadened with decreased complexity. The size of the whole chip including the probe GSG pads is $0.95 \times 0.65 \text{ mm}^2$. The measured results show that the conversion loss is 7.2–11.9 dB for the RF frequency range of 35–95 GHz with an LO power level of 14 dBm and a fixed IF frequency of 1 GHz. In addition, the conversion loss is better than 12 dB for the IF frequency range from DC to 30 GHz under a fixed LO frequency.

Keywords: ultrawide bandwidth, doubly balanced ring mixer (DBRM), Marchand balun, monolithic microwave integrated circuit (MMIC)

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Down-conversion mixers are crucial elements in millimeter-wave (MMW) systems, including radio astronomical receivers, complex electromagnetic environment monitors and measurement instruments [1, 2, 3]. For this type of mixer, achieving both wide RF and IF bandwidths without sacrificing other performances is required. A wide IF bandwidth has many advantages for radio astronomy and electronic warfare. For example, a wide IF bandwidth improves the sensitivity of radar receivers and increases the detection rate of unknown signals in complex electromagnetic environments. On the other hand, a wide RF bandwidth mixer reduces the cost and complexity of receiver systems.

A doubly balanced mixer (DBM) provides wide bandwidth, excellent suppression of even harmonics of RF/LO signals and distinguished port-to-port isolations [4]. In addition, a DBM with diodes does not require DC consumption and achieves higher input P1dB than that of an active mixer [2, 5]. The two most popular types of doubly

balanced mixers (DBMs) are doubly balanced star mixers (DBSMs) and doubly balanced ring mixers (DBRMs). Research on broadband doubly balanced star mixer (DBSM) and doubly balanced ring mixer (DBRM) has been well-developed for decades [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

Because of the inherent configuration and low parasitic IF inductance, a DBSM has wide RF/IF bandwidths [17, 18, 19]. A DBSM with a dual balun was reported in [17]. The proposed mixer achieves a conversion loss of 8.6–12.5 dB in the range from 52 GHz to 68 GHz and an IF bandwidth of DC–12 GHz. However, the baluns used in the mixer are open circuits for even-mode excitation. Thus, this design does not allow the overlap of the RF/LO band and IF band [20].

In contrast to a DBSM, a DBRM has a parallel RF bandwidth. However, the IF bandwidth of a DBRM is limited by the IF extraction structure. Previously, M. Maesel *et al.* designed a 6–18 GHz GaAs DBRM with two coupled-line baluns and four GaAs Schottky diodes [21]. The IF current is extracted from the mixer by a low-pass filter. Nevertheless, the filter introduces discontinuous inductance into the circuit and tremendously limits the IF bandwidth. Maas *et al.* also developed a DBRM that achieved an 18–40 GHz RF bandwidth and a DC–10 GHz IF bandwidth [22]. In this mixer, a two-coupled-line Marchand balun is used to extend the RF bandwidth. Moreover, no low-pass filter is required in the IF extraction design. An additional coupled-line section is used to provide an output for the IF current and effectively broadens the IF bandwidth. However, this section still introduces partly parasitic inductance into the IF path. To a certain extent, the additional section also increases the conversion loss and limits the RF bandwidth. Ref. [23] designed a DBRM with a 26–40 GHz RF bandwidth and a DC–14 GHz IF bandwidth. A three-coupled-line Marchand balun and an additional three-coupled-line IF extraction structure are implemented. The multiple-coupled-line Marchand balun outperforms the traditional two-coupled-line Marchand balun in terms of bandwidth [24, 25, 26]. However, this mixer fails to achieve an RF bandwidth wider than that presented in [22]. In addition, several doubly balanced ring mixers (DBRMs) use a spiral balun to extend the IF bandwidth [27, 28, 29, 30, 31, 32]. The IF current is directly drawn from the RF spiral balun. For example, Ref. [32] presented a DBRM based on two spiral baluns, where the RF bandwidth of the mixer ranges from 6 GHz to 18 GHz, while the IF bandwidth ranges from DC to 8 GHz.

¹School of Instrument and Electronics, North University of China, Taiyuan 030051, China

²China Electronics Technology Instruments Co. Ltd, Qingdao 266555, China

³Technology on Electronic Test & Measurement Laboratory, Qingdao 266555, China

a) nfswxmnk825@163.com

DOI: 10.1587/ele.16.20190602

Received September 27, 2019

Accepted September 30, 2019

Published October 15, 2019

Copyrighted November 12, 2019

Although spiral baluns can reduce the chip size and extend the IF bandwidth of DBRMs, this design has unsatisfactory conversion loss above the V-band.

In conclusion, all these previous studies only focused on expanding either the RF bandwidth or the IF bandwidth. A DBRM with simultaneous wide RF and IF bandwidths is still urgently required. In this study, a broadband monolithic DBRM with a 35–95 GHz RF bandwidth and a DC–30 GHz IF bandwidth is designed. In the proposed mixer, a three-coupled-line Marchand balun and a novel IF extraction structure are utilized to expand the RF and IF bandwidths, respectively. Due to this configuration, the RF/IF bandwidths are extended without sacrificing conversion loss. Moreover, the novel IF extraction structure results in a compact chip size.

2. Design of the mixer configuration

Fig. 1 shows the fundamental configuration of the proposed DBRM, which consists of two three-coupled-line Marchand baluns and a diode ring. The proposed IF extraction structure utilizes two transmission lines of the RF balun to combine the IF current. Then, the IF current is directly extracted from the RF balun. The air-bridges connect the two outside lines of the three-coupled-line Marchand balun. Moreover, the open stub (TL1), which serves as a grounding capacitor, is parallelly connected to the interconnected transmission line of the RF balun to adjust the phase and amplitude balance of the balun. No grounding holes are employed in the balun at the RF port. The virtual ground at point ‘a’ allows the RF balun to provide the differential signals for the diodes. The quarter-wavelength open stub (TL2) of the RF signal enhances the isolation between the RF/LO port and the IF port. The most crucial elements of this work are the design of the passive couplers at the LO port and RF/IF port.

3. Design of the passive couplers

3.1 Design of the broadband Marchand balun

In this work, a three-coupled-line Marchand balun with a pair of air-bridges is used to increase the coupling coefficient and extend the RF bandwidth. Fig. 2 features the structure of the proposed planar Marchand balun, which consists of two cascaded three-coupled-line couplers and an interconnected transmission line. The two outside lines of the couplers are shorted. The Marchand balun acts as the impedance transformer between the input and output ports to provide the differential signals. However, the phase length of the transmission line varies with frequency. Realizing an ideal impedance transformation over the whole operating band is impossible. By balancing the effects of each parameter, the designed Marchand balun can achieve a wider operating bandwidth.

From [26], the calculated model and systematic design procedure for a multiconductor coupled-line Marchand balun are used in this design. The effects of the width and spacing of the coupled line are discussed in this reference. However, the effects of L_1 and L_2 are required for a detailed investigation. Fig. 3 shows the insertion

Fig. 1. Configuration of the proposed broadband DBRM.

Fig. 2. Structure of the proposed Marchand balun.

losses and imbalances of baluns with different L_1 . The frequency range moves toward lower frequencies with increasing L_1 . As shown in Fig. 4, L_2 tremendously affects the imbalance. Nonetheless, the interconnected transmission line of the balun is inevitable.

After iterative designs, the parameters are balanced between the overall circuit design and the balun performance. The detailed parameters of the proposed balun are provided in Table I. Fig. 5(a) shows the simulated amplitudes and phase differences from 40 GHz to 90 GHz. The amplitude differences are less than ± 1 dB, and the phase differences are better than ± 4 degrees. Fig. 5(b) illustrates the simulated insertion losses in the range from 40 GHz to 90 GHz.

Table I. Parameters for the proposed Marchand balun

W_1	8 μm	L_1	280 μm
W_2	10 μm	L_2	50 μm
W_3	8 μm	S_1	6 μm
W_4	10 μm	S_2	6 μm

3.2 Design of the novel IF extraction structure

The IF extraction structure plays a crucial role in a DBRM. In this design, a novel IF signal extraction structure is proposed, and the signal is directly extracted from the RF balun. Fig. 6(a) shows the practical implementation of the proposed structure and the schematic diagram of the signal flow direction. The proposed structure is synthesized by a three-coupled-line Marchand balun and a broadband combiner. Fig. 6(b) displays the structure of the broadband combiner. Fig. 7 shows the broadband characteristics of the combiner. The insertion loss of the combiner

Fig. 3. (a) Simulated amplitudes and phase differences of baluns with different L1. (b) Simulated insertion losses of baluns with different L1. (fixed $W1 = W2 = W3 = 7 \mu\text{m}$, $S1 = S2 = 5 \mu\text{m}$, $L2 = 50 \mu\text{m}$)

Fig. 4. (a) Simulated amplitudes and phase differences of baluns with different L2. (b) Simulated insertion losses of baluns with different L2. (fixed $W1 = W2 = W3 = 7 \mu\text{m}$, $S1 = S2 = 5 \mu\text{m}$, $L1 = 280 \mu\text{m}$)

Fig. 5. (a) Simulated amplitudes and phase differences of the proposed balun. (b) Simulated insertion losses of the proposed balun.

Fig. 6. (a) Practical implementation of the proposed structure and the schematic diagram of the signal flow direction. (b) Structure of the broadband combiner.

Fig. 7. Simulated insertion loss of the broadband combiner.

is better than 3.6 dB in the frequency range of DC-50 GHz. Moreover, the transmission lines of the combiner are reused by the RF balun. By synthesizing the RF balun and the combiner, the proposed structure not only achieves single-to-differential conversion but also extracts an IF signal with broadband characteristics. To extract the IF current, no grounding hole is implemented in this structure to prevent short circuiting of the IF current. A virtual ground makes the RF balun output the differential signals for the diodes.

In addition, the layout of the structure introduces a large phase length for the interconnected transmission line to the RF balun. The balance between the amplitude and phase deteriorates with increasing phase length. Lumped elements have been widely used for balancing Marchand baluns. The shunt capacitance at the terminal of the coupled line does not affect the even-mode impedance, but the phase length of the odd-mode signal increases. In this design, an open stub serving as a shunt capacitor is utilized to offset the negative of the interconnected line and adjust the balance of the RF balun. As shown in Fig. 8, these traditional additional IF extraction structures have been widely used in DBRMs. These traditional structures occupy large chip areas and limit the IF bandwidth. Compared with these traditional structures, the novel IF balun extraction structure is incorporated into the RF balun. The proposed structure utilizes two transmission lines of the RF balun to combine the IF current. Fig. 9 compares the insertion loss of three IF extraction structures. The novel IF extraction structure exhibits better insertion loss than the other types of structures in the frequency range from DC to 50 GHz. In summary, this novel structure achieves lower insertion loss and reduces the size of the chip by approximately 20–30%. This result indicates that the proposed structure can achieve an ultrawide IF bandwidth.

Fig. 8. (a) Coupled-line section that acts as the IF extraction structure and the schematic diagram of the signal flow direction. (b) Low-pass filter structure acts as the IF extraction structure and the schematic diagram of the signal flow direction.

Fig. 9. (a) Simulated insertion losses of the proposed structure and the Type-1 structure. (b) Simulated insertion loss of the Type-2 structure.

4. Mixer circuit results and discussion

The DBRM was fabricated using the WIN 0.1 μm GaAs pHEMT monolithic microwave integrated circuit (MMIC) process. A photograph of the chip is shown in Fig. 10. The operating frequency range of the proposed mixer contains several waveguide frequency bands. Subject to the test conditions, the measurement setups are divided into two parts. When the RF frequency is below 70 GHz, the 1.85 mm coaxial cavity of the DBRM is used for measurement. For frequencies from 71 GHz to 95 GHz, the W-10 waveguide cavity of the mixer is used for measurement. Fig. 11 shows the block diagrams and test platforms of the proposed mixer with different packages. Fig. 12 shows the simulated and measured conversion losses of the mixer. The mixer achieves conversion losses of 7.2–11.9 dB for RF frequencies from 35 GHz to 95 GHz, the available bandwidth is above 60 GHz and the RF fractional bandwidth is as high as 90%. The measured results for the DBRM are well consistent with the simulated results.

Fig. 13 shows the conversion loss versus the LO power at fixed RF frequencies of 35 GHz, 40 GHz, 75 GHz and 90 GHz. The conversion loss is minimized when the input LO power reaches 14 dBm. Fig. 14 indicates the

Fig. 10. Photograph of the proposed DBRM.

Fig. 11. (a) Block diagram and test platform of the coaxial cavity. (b) Block diagram and test platform of the waveguide cavity.

Fig. 12. Conversion loss versus the RF frequency at the LO power of 14 dBm and fixed IF frequency of 1 GHz.

conversion loss versus the IF frequency. The measurements are performed at an LO power of 14 dBm and LO frequencies of 36 GHz, 38 GHz and 40 GHz. The DBRM achieves conversion losses of 7.8–12 dB when the IF frequency varies from DC to 30 GHz. In fact, the simulated results show conversion losses better than 12 dB in the range from DC to 50 GHz. However, the mixer is only measured to 30 GHz because of the limited test conditions. Fig. 15 shows the input P1dB point of the DBRM. When the LO power is 14 dBm, the measured P1dB is 11–12 dBm at RF frequencies of 35 GHz, 75 GHz and 90 GHz. Fig. 16 presents the LO-to-RF, LO-to-IF and RF-to-IF isolations of the mixer at RF frequencies of 30–100 GHz. The LO-to-RF isolation over the whole RF frequency band ranges from 24 to 50 dB. The LO-to-IF isolation varies between 24 dB and 70 dB in the range from 30 GHz to 100 GHz. The RF-to-IF isolation is poor below 75 GHz, and the measured data

range from 14 to 34 dB. However, the isolation is 30–61 dB above 75 GHz.

Table II compares the measured performance with the reported performances of several broadband fundamental mixers. The proposed mixer shows the merit of large RF/IF bandwidths for the MMW band. Furthermore, a figure-of-merit (FOM) is defined to impartially compare the cited works [33]. The proposed FOM includes all the common indicators for mixers.

$$FOM = -CL + 20 \log\left(\frac{BW(RF)}{1 \text{ GHz}}\right) + 20 \log\left(\frac{BW(IF)}{1 \text{ GHz}}\right) + 10 \log\left(\frac{P_{1dB}}{1 \text{ dBm}}\right) - 10 \log\left(\frac{LO(\text{power})}{1 \text{ dBm}}\right) \quad (1)$$

where CL denotes the minimum conversion loss, $BW(RF)$ represents the RF bandwidth, $BW(IF)$ is the IF bandwidth and $LO(\text{power})$ is the LO power. A higher FOM indicates better mixer performance.

Table II. Comparison of published broadband fundamental mixers

Reference	[2]	[5]	[17]	[28]	This work
Topology	Single balance mixer	Cascode mixer	Star mixer	Ring mixer	Ring mixer
Technology	90 nm CMOS	0.1 μm pHEMT	0.15 μm pHEMT	0.15 μm pHEMT	0.1 μm pHEMT
RF Freq. (GHz)	30–90	67–90	52–68	16–40	35–95
IF Freq. (GHz)	DC–26	4–16	DC–12	DC–7	DC–30
LO Power (dBm)	4.2 (active)	9.5	12	14	14
Conversion Loss (dB)	5.8–8	8 (best)	8.6–12.5	8–13	7.2–11.9
LO-to-RF Isola. (dB)	30–50	N.A	23–36	35–50	24–50
LO-to-IF Isola. (dB)	N.A	N.A	18–27	27–44	24–70
RF-to-IF Isola. (dB)	N.A	N.A	31–43	13–35	14–61
Input P1dB (dBm)	2	3	7.7	14	11
Chip Size (mm^2)	0.389	N.A	0.40	1	0.62
FOM (dB)	54.8	35.8	35.1	36.5	56.8

5. Conclusion

In this letter, a monolithic DBRM that simultaneously achieves ultrawide RF and IF bandwidths has been presented. Two multiple-coupled-line Marchand baluns are utilized to broaden the RF bandwidth. A novel IF extraction structure is designed to extend the IF bandwidth and reduce the area of the chip. Moreover, the mixer achieves port-to-port isolations and P1dB performance comparable with those in previous works. These unique properties can

Fig. 13. Measured conversion loss versus the LO power at RF frequencies of 35 GHz, 40 GHz, 75 GHz and 90 GHz and a fixed IF frequency of 1 GHz.

Fig. 14. Measured conversion loss versus the IF frequency at an LO power of 14 dBm and LO frequencies of 36 GHz, 38 GHz and 40 GHz.

Fig. 15. Measured conversion loss versus the RF power at RF frequencies of 35 GHz, 75 GHz and 90 GHz.

Fig. 16. Measured isolations versus RF frequencies from 30 GHz to 100 GHz.

be widely applied to radio astronomical receivers, measurement instruments and radar electronic warfare systems in the MMW range.

Acknowledgments

This work was funded by the National Key R&D Program of China (2018YFF0109702) and the Innovation Fund of the China Electronics Technology Group Corporation (KJ1801008). The authors would like to thank Guangwei Du, Xiaolin Cheng, and Mo Wang from China Electronics Technology Instruments Co., Ltd., for their valuable assistance with the measurement of the proposed DBRM.

References

- [1] C. E. Tong, *et al.*: “Wideband SIS receiver development for the submillimeter array,” International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz) (2015) 1 (DOI: [10.1109/IRMMW-THz.2015.7327696](https://doi.org/10.1109/IRMMW-THz.2015.7327696)).

- [2] Y.-C. Wu, *et al.*: “A novel 30–90 GHz singly balanced mixer with broadband LO/IF,” *IEEE Trans. Microw. Theory Techn.* **64** (2016) 4611 (DOI: [10.1109/TMTT.2016.2622708](https://doi.org/10.1109/TMTT.2016.2622708)).
- [3] A. E. Spezio, *et al.*: “Electronic warfare systems,” *IEEE Trans. Microw. Theory Techn.* **50** (2002) 633 (DOI: [10.1109/22.989948](https://doi.org/10.1109/22.989948)).
- [4] S. A. Mass: *Microwave Mixers* (Artech House, USA, 1993) 2nd ed. 238.
- [5] J.-H. Hu, *et al.*: “E-band mixer with IP1dB design consideration for radio astronomical instrumentation,” *IEEE Microw. Compon. Lett.* **28** (2018) 452 (DOI: [10.1109/LMWC.2018.2813886](https://doi.org/10.1109/LMWC.2018.2813886)).
- [6] M. Yu, *et al.*: “Ka/Q-band doubly balanced MMIC mixers with low lo power,” *IEEE Microw. Compon. Lett.* **10** (2000) 424 (DOI: [10.1109/75.877233](https://doi.org/10.1109/75.877233)).
- [7] H. Morkner, *et al.*: “A 18–45 GHz double-balanced mixer with integrated LO amplifier and unique suspended broadside-coupled balun,” *IEEE Gallium Arsenide Integrated Circuit (GaAs IC) Symposium* (2003) 267 (DOI: [10.1109/GAAS.2003.1252409](https://doi.org/10.1109/GAAS.2003.1252409)).
- [8] K.-W. Yeom and D.-H. Ko: “A novel 60-GHz monolithic star mixer using gate-drain-connected pHEMT diodes,” *IEEE Trans. Microw. Theory Techn.* **53** (2005) 2435 (DOI: [10.1109/TMTT.2005.850402](https://doi.org/10.1109/TMTT.2005.850402)).
- [9] J.-C. Jeong, *et al.*: “An active IF balun for a doubly balanced resistive mixer,” *IEEE Microw. Compon. Lett.* **19** (2009) 224 (DOI: [10.1109/LMWC.2009.2015503](https://doi.org/10.1109/LMWC.2009.2015503)).
- [10] X. Cao, *et al.*: “Design of a double balanced mixer based on a novel planar UWB balun,” *IEICE Electron. Express* **13** (2016) 20160026 (DOI: [10.1587/elex.13.20160026](https://doi.org/10.1587/elex.13.20160026)).
- [11] H.-L. Kao, *et al.*: “67–80 GHz double-balanced Gilbert-cell mixer in 0.1 μm GaAs pHEMT technology,” *Electron. Lett.* **52** (2016) 291 (DOI: [10.1049/el.2015.3107](https://doi.org/10.1049/el.2015.3107)).
- [12] A. Hamed, *et al.*: “6–12 GHz MMIC double-balanced upconversion mixer based on graphene diode,” *IEEE/MTT-S International Microwave Symposium* (2018) 674 (DOI: [10.1109/MWSYM.2018.8439211](https://doi.org/10.1109/MWSYM.2018.8439211)).
- [13] T. Zhang, *et al.*: “Mixing it up: A double-balanced mixer with wide RF and IF bandwidth,” *IEEE Microw. Mag.* **19** (2018) 106 (DOI: [10.1109/MMM.2017.2759659](https://doi.org/10.1109/MMM.2017.2759659)).
- [14] C.-M. Lin, *et al.*: “A 16–44 GHz compact doubly balanced monolithic ring mixer,” *IEEE Microw. Compon. Lett.* **18** (2008) 620 (DOI: [10.1109/LMWC.2008.2002464](https://doi.org/10.1109/LMWC.2008.2002464)).
- [15] J. Kim, *et al.*: “W-band double-balanced down-conversion mixer with Marchand baluns in silicon-germanium technology,” *Electron. Lett.* **45** (2009) 841 (DOI: [10.1049/el.2009.1128](https://doi.org/10.1049/el.2009.1128)).
- [16] H.-L. Kao, *et al.*: “A 30–65 GHz wideband double-balanced Gilbert-cell mixer using GaAs pHEMT technology,” *Microw. Opt. Technol. Lett.* **54** (2012) 1196 (DOI: [10.1002/mop.26773](https://doi.org/10.1002/mop.26773)).
- [17] T. Yang, *et al.*: “A compact V-band star mixer using compensated overlay capacitors in dual baluns,” *IEEE Microw. Compon. Lett.* **17** (2007) 537 (DOI: [10.1109/LMWC.2007.899321](https://doi.org/10.1109/LMWC.2007.899321)).
- [18] C. Lin, *et al.*: “A 26–38 GHz monolithic doubly balanced mixer,” *IEEE Microw. Compon. Lett.* **18** (2008) 623 (DOI: [10.1109/LMWC.2008.2002465](https://doi.org/10.1109/LMWC.2008.2002465)).
- [19] C.-C. Kuo, *et al.*: “Novel miniature and broadband millimeter-wave monolithic star mixers,” *IEEE Trans. Microw. Theory Techn.* **56** (2008) 793 (DOI: [10.1109/TMTT.2008.919063](https://doi.org/10.1109/TMTT.2008.919063)).
- [20] S. A. Maas: *Nonlinear Microwave and RF Circuits* (Artech house, Inc, USA, 2003) 2nd ed. 353.
- [21] M. Maesel, *et al.*: “A double balanced 6–18 GHz GaAs MMIC mixer,” *GaAs IC Symposium Technical Digest* (1991) 49 (DOI: [10.1109/GAAS.1991.172631](https://doi.org/10.1109/GAAS.1991.172631)).
- [22] S. A. Maas, *et al.*: “An 18–40 GHz monolithic ring mixer,” *IEEE Radio Frequency Integrated Circuits (RFIC) Symposium. Digest of Papers* (1998) 29 (DOI: [10.1109/RFIC.1998.682041](https://doi.org/10.1109/RFIC.1998.682041)).
- [23] L. Qin, *et al.*: “A millimeter-wave monolithic doubly balanced diode mixer,” *J. Semicond.* **31** (2010) 035005 (DOI: [10.1088/1674-4926/31/3/035005](https://doi.org/10.1088/1674-4926/31/3/035005)).
- [24] W. Pei-Si, *et al.*: “A millimeter-wave ultra-compact broadband diode mixer using modified Marchand balun,” *European Gallium Arsenide and Other Semiconductor Application Symposium* (2005) 349.
- [25] J. Schellenberg and D.-K. Hien: “Low-loss, planar monolithic baluns for K/Ka-band applications,” *IEEE/MTT-S International Microwave Symposium* (1999) 1733 (DOI: [10.1109/MWSYM.1999.780306](https://doi.org/10.1109/MWSYM.1999.780306)).
- [26] C. Lin, *et al.*: “Analysis of multiconductor coupled-line Marchand baluns for miniature MMIC design,” *IEEE Trans. Microw. Theory Techn.* **55** (2007) 1190 (DOI: [10.1109/TMTT.2007.897689](https://doi.org/10.1109/TMTT.2007.897689)).
- [27] J.-C. Kao, *et al.*: “V-band dual-conversion down-converter with Schottky-diode ring-mixer using 0.35 μm SiGe BiCMOS process,” *Asia-Pacific Microwave Conference* (2015) 1 (DOI: [10.1109/APMC.2015.7411813](https://doi.org/10.1109/APMC.2015.7411813)).
- [28] H. Chuang, *et al.*: “A K- to Ka-band broadband doubly balanced monolithic ring mixer,” *IEEE Microw. Compon. Lett.* **18** (2008) 401 (DOI: [10.1109/LMWC.2008.922648](https://doi.org/10.1109/LMWC.2008.922648)).
- [29] J.-H. Chen, *et al.*: “A 15–50 GHz broadband resistive FET ring mixer using 0.18- μm CMOS technology,” *IEEE/MTT-S International Microwave Symposium* (2010) 784 (DOI: [10.1109/MWSYM.2010.5517957](https://doi.org/10.1109/MWSYM.2010.5517957)).
- [30] Y. Zhao, *et al.*: “Design and performance of a broadband millimeter-wave MMIC mixer,” *International Conference on Computational Problem-Solving (ICCP)* (2012) 383 (DOI: [10.1109/ICCP.2012.6384327](https://doi.org/10.1109/ICCP.2012.6384327)).
- [31] M. Yang and L. Wang: “An 18 to 40 GHz double balanced MMIC mixer using GaAs technology,” *IEEE International Conference on Communication Problem-solving* (2014) 556 (DOI: [10.1109/ICCP.2014.7062345](https://doi.org/10.1109/ICCP.2014.7062345)).
- [32] T. Zhang, *et al.*: “A GaAs passive mixer with an ultra-wide IF bandwidth,” *IEICE Electron. Express* **13** (2016) 20160973 (DOI: [10.1587/elex.13.20160973](https://doi.org/10.1587/elex.13.20160973)).
- [33] S. Zhang, *et al.*: “A compact D-band monolithic APDP-based sub-harmonic mixer,” *Solid-State Electron.* **137** (2017) 62 (DOI: [10.1016/j.sse.2017.07.001](https://doi.org/10.1016/j.sse.2017.07.001)).