Progress In Electromagnetics Research Letters, Vol. 79, 9–15, 2018

Design of a Broadband Fixed IF Sub-Harmonic Mixer at Ka Band

Jianhong Hou*, Heng Xie, Xing Li, Hongtao Zhang, Minghua Zhao, and Yong Fan

Abstract—This paper describes the design of a broadband, fixed-IF, high efficiency single subharmonic mixer at Ka-band. The co-simulation between HFSS and ADS is applied to the modeling of the mixer. In order to improve the accuracy of simulation, the diode model is divided into passive linear model and active nonlinear model. On this basis, a global accurate equivalent circuit model of mixer is proposed and verified by testing data. The circuit of the presented mixer printed on the substrate of Rogers RT/Duroid 3003 is mounted in a waveguide block. When the fixed IF frequency is set at 1.5 GHz, measured results show that the conversion loss is less than 8 dB over the RF bandwidth from 25 GHz to 39 GHz with 12 dBm of local oscillator power. The minimum conversion loss of 6.2 dB is measured at 28 GHz. The measured isolation between LO and IF, LO and RF is over 23 dB. The measured isolation between IF and RF is over 20 dB. Good isolation is achieved.

1. INTRODUCTION

Millimeter wave band like Ka-band is widely used in the field of satellite communications for its wide bandwidth and fast communication speed [1]. The mixer is an important part of radar and microwave measurement systems. In the measurement systems, the frequency of IF signal is usually fixed. Therefore, the back-end circuit can be well designed. Most mixers with fixed frequency LO, the frequency of IF signals changes with RF signals. However, the proposed mixer in this work has fixed IF frequency and broadband matching of LO and RF. The IF port can be sampled directly by back-end circuit. Additionally, it can avoid second times of down-conversion and further reduce the volume of the systems.

Harmonic mixers require LO signals of only 1/N the frequency of the RF (where N is the harmonic order) [2]. It can ensure good isolation between RF and LO. However, conversion loss increases compared with fundamental mixers. Considering that the low fixed-IF frequency is set at 1.5 GHz, to obtain better isolation and low conversion loss, sub-harmonic mixer becomes a better choice. The local oscillator frequency of Ka-band sub harmonic mixer is located at Ku-band, and the waveguide size of this band is larger. To ensure good broadband matching and reduce module volume, substrate integrated waveguide (SIW) microstrip transition is adopted. SIW can realize the propagation characteristics of the traditional metal waveguide on the substrate, and it has many advantages such as low radiation, low insertion loss, high Q value, high power capacity and small volume for rectangular waveguide and microstrip device. Through the good matching networks of RF and LO, the conversion loss is less than 8 dB over the bandwith from 26 GHz to 39 GHz when fixed IF is 1.5 GHz. Therefore, characteristic of wide band and high efficiency can be achieved.

Received 8 June 2018, Accepted 4 September 2018, Scheduled 27 September 2018
* Corresponding author: Jianhong Hou (jianhonghou@126.com).
The authors are with the University of Electronic Science and Technology of China, Chengdu, China.

2. MIXER DESIGN

The anti-parallel balanced circuit is shown in Fig. 1. These two diodes are anti-parallel as to input and output circuits which make the odd-harmonic mixing components exist in the internal circulation of the diode pair, while even-harmonic mixing components exist outside. The suppression to odd harmonics depends on the uniformity of the diodes and the symmetry of the circuit.

Accurate diode equivalent circuit is the key of mixer design [3]. The diode chip used in this work is MA4E1310 produced by MACOM. In millimeter wave band, the geometry of the diode chip causes significant high frequency parasitic effect and affects the performance of the mixer greatly. This work divides diode model into passive linear model and active nonlinear equivalent model. Important parameters of the active nonlinear equivalent circuit model are obtained through the datasheet. It is built in ADS. Then, three-dimensional (3D) EM model of diode chip is built in High Frequency Structure Simulator (HFSS). The S-parameter extracted from 3D EM model can describe the high frequency parasitic characteristic. The active nonlinear equivalent circuit in ADS shows the nonlinear behavior of the Schottky junction. Fig. 2 shows the diode nonlinear equivalent model. Fig. 3 shows the 3D EM diode model mounted on the pad.

The principle circuit of the subharmonic mixer is shown in Fig. 4. The mixing circuit consists of an RF probe [4], an LO SIW transition [5], an idle energy recovery network [6], an IF filter, the matching networks, a compensation solder pad and a pair of Schottky diodes.

To minimize the loss of the RF signal and achieve broadband matching in Ka-band, the WR-28 waveguide and 1/4 wavelength microstrip line matching networks are used. The LO signal is fed by SIW transition because the size of standard waveguide Ku-band is large 15.799 mm ∗ 7.899 mm. It has

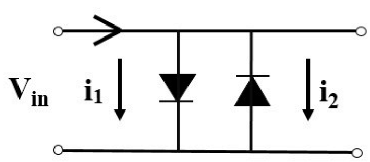


Figure 1. The anti-parallel balanced circuit.

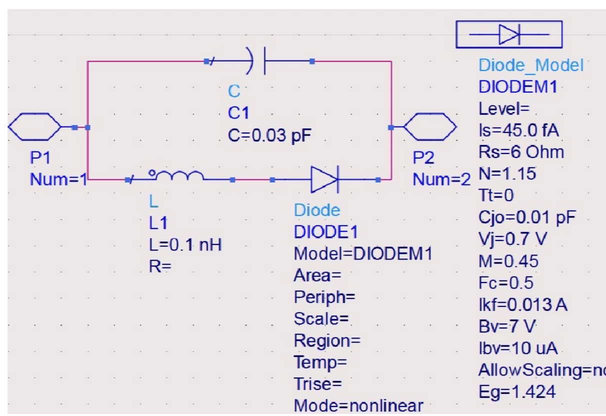
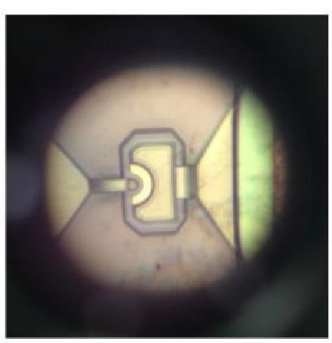
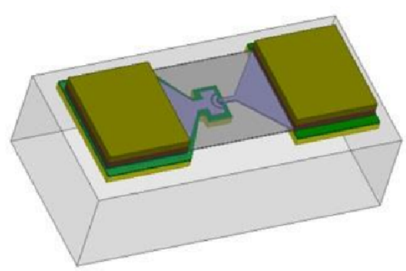


Figure 2. The diode nonlinear equivalent model.



(a)



(b)

Figure 3. (a) Optical microscope image of diode, (b) 3D model of diode.

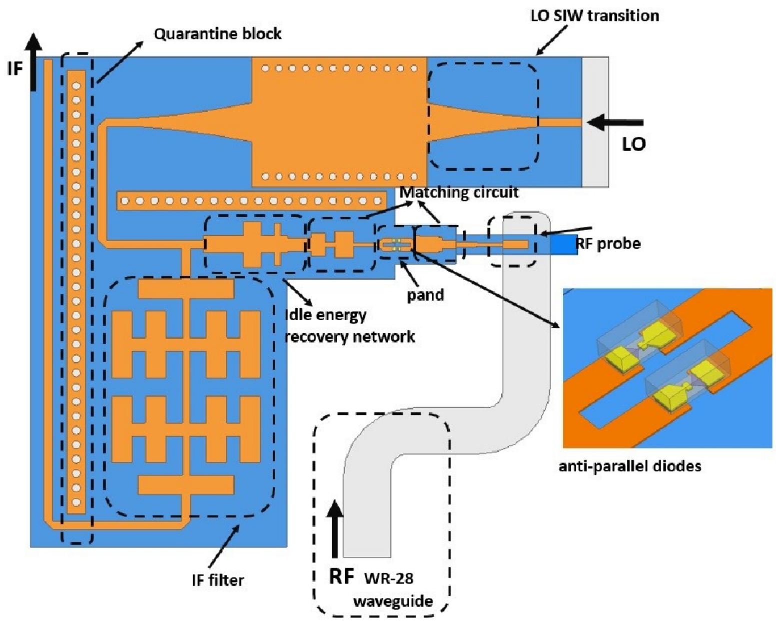


Figure 4. Structure of the mixer.

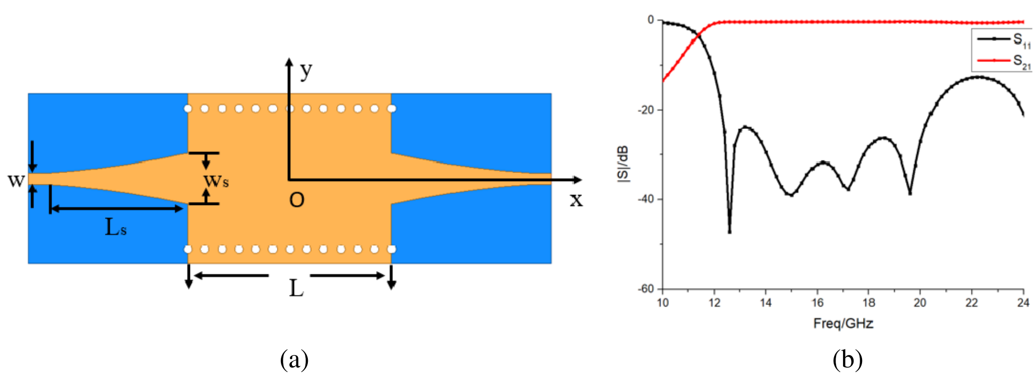


Figure 5. (a) Exponential microstrip gradient structure, (b) simulated results.

advantages of both rectangular waveguide and microstrip device to achieve broadband matching of the LO. In addition, the volume of circuit can also be reduced. The transition of SIW with microstrip is one of the principal problems in studying SIW. In order to heighten the energy transmission efficiency between them, one exponential microstrip gradient structure is designed by the analysis of the impedance matching of them. The structure is shown in Fig. 5. The exponential function is $y = Ae^{m(x-x_0)}$. From Fig. 5, $A = w_s/2$, $x_0 = L/2$. The performance of the structure is greatly influenced by the transition length "Ls". The exponential coefficient "m" affects the width of microstrip line "w_s". The simulation results are shown in Fig. 5. The simulated return loss is better than 25 dB from 12 GHz to 20 GHz, which can ensure great energy transmission efficiency.

By designing a reasonable idle frequency energy recovery circuit at the LO, the idle energy including the RF energy and odd harmonic energy of the LO is recycled to decrease the conversion loss of the mixer.

The solder pad is used to connect the nonlinear device and linear circuit [7]. However, with the increase of working frequency, the influence of parasitic parameters introduced by pads on the performance of the whole circuit is also affected. In order to improve the design reliability and improve the performance of the mixer, a compensation solder pad for antiparallel diode is developed to compensate the capacitance resulted by the pad of the nonlinear device. By using ADS to extract the impedance of diodes at fundamental and secondharmonic frequency, the broadband matching networks of RF and LO can be reasonably designed.

The filter with BCMRC is designed to get the IF signal from the mixer and ensure good isolation between IF and LO [8, 9]. It exhibits remarkable wide stopband and slow-wave characteristics. Simulated results of the filter are shown in Fig. 6. In actual use, these three ports of the mixer have T font distribution to facilitated circuit installation.

The s-parameters of the passive circuit models are exported from HFSS and then imported into ADS. In the Advanced Design System, the s-parameters of the passive circuit are imported into Harmonic Balance Simulator where we model the nonlinear behavior of the diode pair. Through continuous optimization, the mixer gets the optimum performance.

The output terminal of the filter is extended by 50 Ohm microstrip line so that the three ports have T font distribution. To avoid cavity resonance, two isolation blocks are added to separate the cavity.

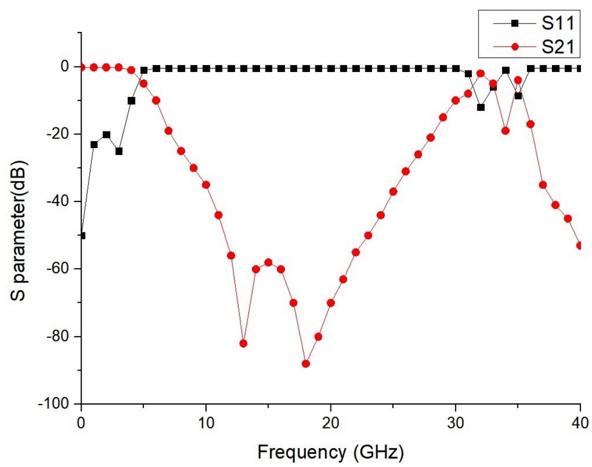
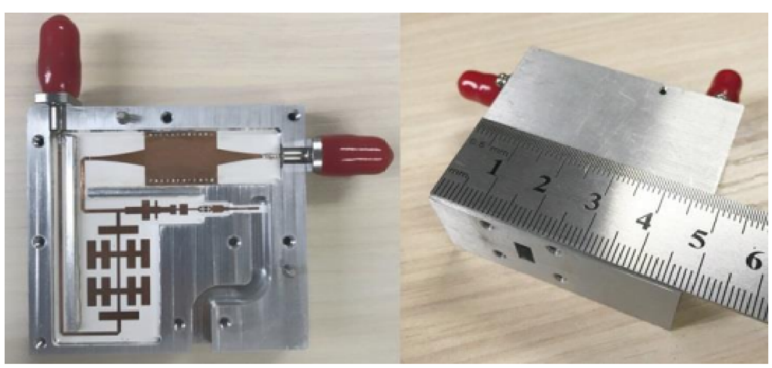


Figure 6. The simulated results of IF low pass filter for CMRC.



(a) (b)

Figure 7. The fabrication of the proposed circuit. (a) Inside view of the assembled bottom block, (b) the photograph of the mixer.

3. FABRICATION AND MEASUREMENT

The circuit of the presented mixer is patterned on a substrate of Rogers RT/Duroid 3003 with a permittivity of 3 and thickness of 254 µm followed with a photolithography process. The E-Plane cut split-block waveguide is milled in aluminum and the LO and IF part connected to the SMA connector.

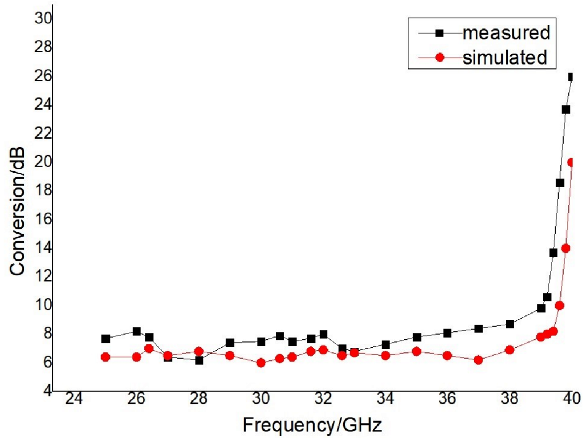


Figure 8. Comparison of conversion loss between simulated result and measred result.

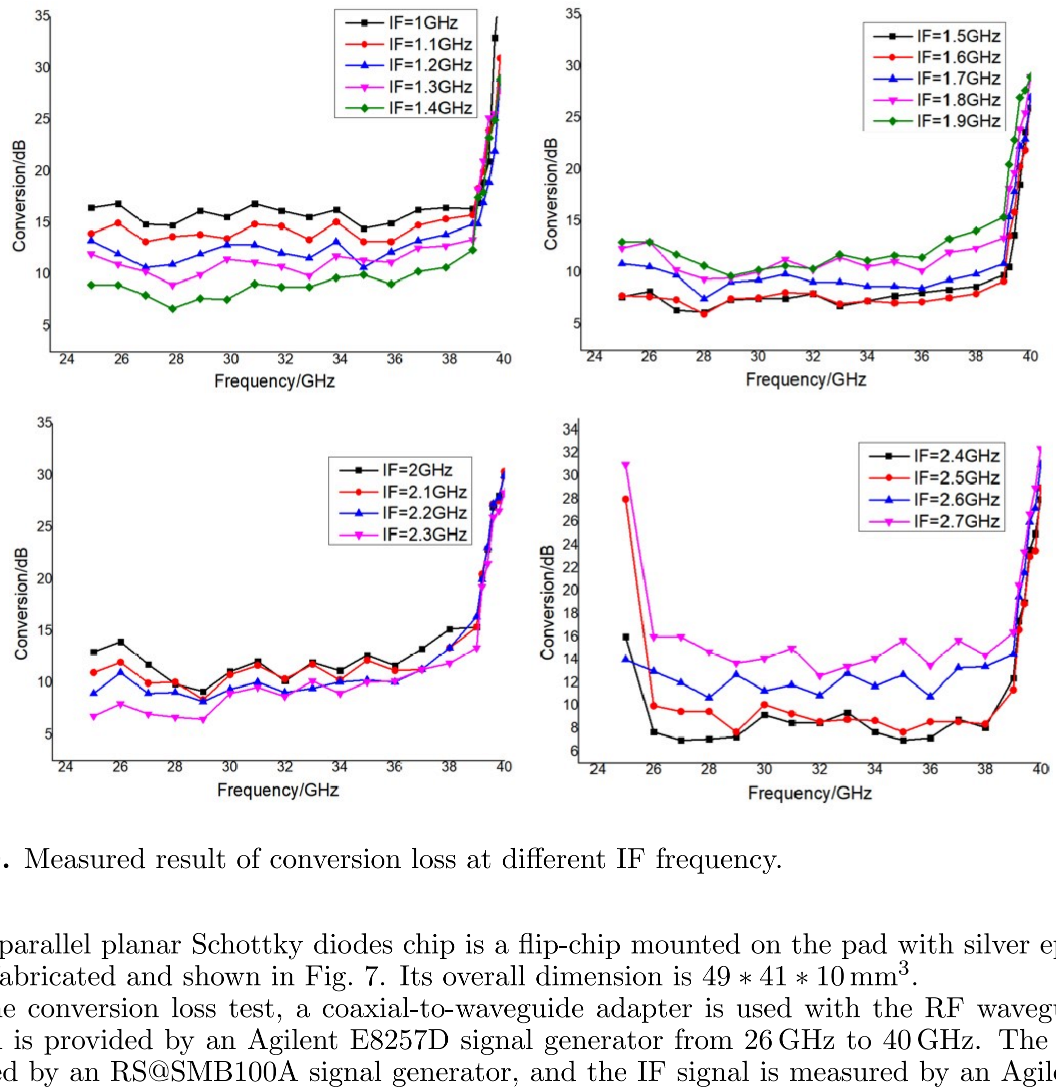


Figure 9. Measured result of conversion loss at different IF frequency.

The anti-parallel planar Schottky diodes chip is a flip-chip mounted on the pad with silver epoxy. The mixer is fabricated and shown in Fig. 7. Its overall dimension is $49 * 41 * 10\,\text{mm}^3$.

In the conversion loss test, a coaxial-to-waveguide adapter is used with the RF waveguide. The RF signal is provided by an Agilent E8257D signal generator from 26 GHz to 40 GHz. The LO signal is provided by an RS@SMB100A signal generator, and the IF signal is measured by an Agilent 8257D spectrum analyzer.

The comparison of conversion loss between simulated results and testing results is shown in the Fig. 8. The results show that the testing data and simulated data are consistent. The accuracy

Table 1. Comparison between the performance of this design and other products.

product	mixing style	frequency of RF	frequency of LO	conversion loss	test style
our paper	subharmonic	25–39 GHz	11.75–18.75 GHz	7–8 dB	fixed IF
paper [10]	subharmonic	35–37 GHz	35 GHz	6.5–7.5 dB	fixed LO
paper [11]	subharmonic	24–44 GHz	12–22 GHz	13–14.5 dB	fixed IF
paper [12]	subharmonic	27–30 GHz	8–9.4 GHz	8.5–10.5 dB	fixed IF
paper [13]	subharmonic	30–40 GHz	14 GHz	8–10 dB	fixed LO
paper [14]	subharmonic	18–26.5 GHz	15 GHz	7.5–10.5 dB	fixed LO

of the diode equivalent circuit has been verified. The above experimental results achieve the design expectation of the Ka band broadband fixed IF sub harmonic mixer. Our design has good performance compared with other products in the same frequency band. Table 1 shows the comparison between the performances of our design and other products.

The measured results of conversion loss are illustrated in Fig. 9 with the LO power level of 12 dBm and the IF frequency fixed from 1 GHz to 2.7 GHz. The results show that the conversion loss is below 15 dB from 25 GHz to 39 GHz when the fixed IF frequency is from 1.1 GHz to 2.6 GHz. The conversion loss is less than 8 dB from 25 GHz to 39 GHz when the IF frequency is fixed at 1.5 GHz and 1.6 GHz.

The measured isolation is illustrated in Fig. 10. Isolation between LO and RF, LO and IF is over 23 dB, Isolation between IF and RF is over 20 dB. Respectively good isolations have been achieved.

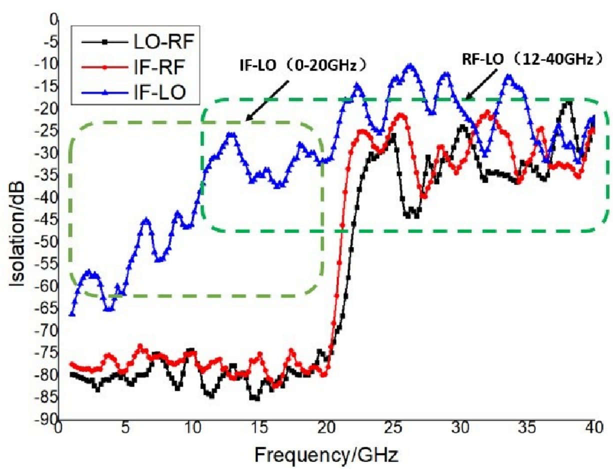


Figure 10. Measured isolation.

4. CONCLUSION

With the field-circuit co-simulation method, a broadband, high efficiency, fixed-IF subharmonic mixer at Ka-band is designed in this work, based on the accurate passive linear model and active nonlinear model. The measured results show that the optimum conversion loss of the mixer is less than 8 dB over the bandwidth from 25 GHz to 39 GHz when the IF frequency is fixed at 1.5 GHz. The measured results are in accordance with the simulation results. The accuracy and feasibility of the model discussed are verified in this article. A reasonable matching network and idle energy recovery network are adopted to achieve good isolation among the three ports and prevent port power leakage.

REFERENCES

1. Lin, S., L. D. Zhu, and Y. T. Guo, "Distribution characteristics and performance simulations of rain attenuation at Ka band for satellite communications," *GSMM*, 579–582, 2012.
2. Cheng, W., X. J. Deng, and M. Li, "110–170 GHz sub-harmonic mixer based on Schottky barrier diodes," *ICMMT*, Vol. 1, 1–4, 2012.
3. Chen, Z. H., J. P. Xu, and D. Z. Ding, "An accurate broadband equivalent circuit model of millimeter wave planar Schottky varistor diodes," *ICMMT*, Vol. 1, 1–4, 2012.
4. Li, K., M. H. Zhao, and Y. Fan, "A W band low-loss waveguide-to-microstrip probe transition for millimeter-wave applications," *MMWCST*, 1–3, 2012.
5. Liu, Z. and G. B. Xiao, "A new transition for SIW and microstrip line," *APMC*, 948–950, 2014.
6. Zhong, F. Q., B. Zhang, and Y. Fan, "A broadband W-band subharmonic mixers circuit based on planar Schottky diodes," *2012 International Conference on Industrial Control and Electronics Engineering (ICICEE)*, 792–794, October 04, 2012.
7. Liu, Y., M. Zhao, Z. He, and Z. Zhu, "A high efficiency balanced frequency tripler incorporating compensation structure for millimeter-wave application," *Progress In Electromagnetics Research C*, Vol. 59, 79–88, 2015.
8. Li, K., M. Zhao, Y. Fan, Z. B. Zhu, and W.-Z. Cui, "Compact lowpass filter with wide stopband using novel double-folded scmrc structure with parallel open-ended stub," *Progress In Electromagnetics Research Letters*, Vol. 36, 77–86, 2013.
9. Yum, T. Y., Q. Xue, and C. H. Chan, "Novel subharmonically pumped mixer incorporating dual-band stub and in-line SCMRC," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, 2538–2547, 2003.
10. Kumar, G. A. and A. Kumar, "Low conversion loss Ka-band suspended stripline mixer with low LO power," *IEEE Applied Electromagnetics Conference (AEMC)*, 1–2, 2013.
11. Kawakami, K., M. Shimozawa, and H. Ikematsu, "A millimeter-wavebroadband monolithic even harmonic image rejection mixer," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, 1443–1446, 1998.
12. Bhavsar, M. L., R. Sharma, and A. Bhattacharya, "Monolithic Ka to Ku-band all balanced sub-harmonic resistive PHEMT mixer for satellite transponder," *IEEE Microwave and Wireless Components Letters*, Vol. 25, 316–318, 2015.
13. Wen, W. J., M. Gao, B. Song, and J. Xun, "Design of a Ka-band GaAs MMIC broadband single-balanced mixer," *Semiconductor Technology*, Vol. 25, 661–665, 2013.
14. Li, K., "Development of a millimeter wave ultra-wideband subharmonically pumped mixer," *Telecommunication Engineering*, Vol. 54, 338–342, 2014.