第 38 卷第 6 期
2019 年 12 月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 38, No. 6
December, 2019

文章编号: 1001-9014(2019)06-0695-06

DOI: 10. 11972/j. issn. 1001-9014. 2019. 06. 003

Design of a 670 GHz fourth-harmonic mixer based on Schottky diode

JI Guang-Yu[1,2], ZHANG De-Hai[1*], MENG Jin[1], YAO Chang-Fei[3]

(1. Key Laboratory of Microwave Remote Sensing, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. School of Electronic and Information Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China)

Abstract: For pre-research on ice cloud detection equipment, the design and test of a low conversion loss (CL) 4th-harmonic mixer working at the central frequency of 670 GHz based on an anti-parallel Schottky diode are presented. In order to improve the mixing efficiency, a two-stage local-oscillator (LO) compact-microstrip-resonate-cell (CMRC) low-pass-filter (LPF) is utilized to suppress the second mixing item ($f = \left|2*f_{LO} - f_{RF}\right|$), the third harmonic of LO signal ($f = 3*f_{LO}$), and RF signal. The LO frequency is only one-quarter of the RF frequency which significantly reduces the complexity and cost of the LO chain. The measurement result shows that the Single-Side-Band (SSB) conversion loss is between 16. 7 dB to 22. 1 dB from 640 GHz to 700 GHz at room temperature. The minimum conversion loss is 16. 8 dB at the RF frequency of 665 GHz.

Key words: terahertz mixer, Schottky diode, fourth-harmonic, compact-microstrip-resonate-cell

PACS: 07. 57. Kp, 84. 30. r, 84. 30. Qi, 84. 30. Vn, 85. 30. De

基于肖特基二极管的四次谐波混频器

纪广玉[1,2], 张德海[1*], 孟 进[1], 姚常飞[3]

(1. 中国科学院国家空间科学中心 微波遥感技术重点实验室,北京 100190;
2. 中国科学院大学,北京 100049;
3. 南京信息工程大学 电子与信息工程学院,江苏 南京 210044)

摘要:针对冰云探测设备的预研,详细介绍了一款基于肖特基二极管的低变频损耗670 GHz四次谐波混频器.为了提升混频效率,采用两级紧凑微带共振单元(CMRC)本振低通滤波器来抑制射频信号、本振三次谐波及二次谐波混频产物.由于本振频率仅为射频频率的四分之一,大大降低了本振链路的复杂度和成本.测试结果表明,在640~700 GHz频带内单边带变频损耗为16.7~22.1 dB,在665 GHz最优单边带变频损耗为16.8 dB.

关 键 词:太赫兹混频器;肖特基二极管;四次谐波;紧凑微带共振单元(CMRC)

中图分类号:TN454, TN773.2　　**文献标识码**:A

Introduction

Nowadays, Terahertz technology has been extensively applied in remote sensing[1], radar[2], wireless communication[3], radio astronomy[4], and biomedical[5]. Ice clouds detection is an important part of terahertz remote sensing because it make essential contributions to Earth's atmosphere radiative transfer process and the water cycle with the important location above and below the Troposphere[6]. For ice cloud particles with a size of several hundred microns, the best observation effect is in the terahertz band[7]. The terahertz ice cloud observation system frequency is selected at atmospheric windows cover 183~874 GHz[8-11]. Observes operating at this frequency offer perspective detection at small ice partial and distribution compared with meteorological detection equip-

Received date: 2019- 06- 10, **revised date**: 2019- 09- 18　　**收稿日期**:2019- 06- 10,**修回日期**:2019- 09- 18

Foundation items: Supported by the National Key Research and Development Program of China (2017YFC0803601)

Biography: JI Guang-Yu(1992-), male, Xinxiang, China. Research area involves solid-state terahertz circuit and terahertz applications. E-mail: guangyuji1@163. com

* **Corresponding author**: E-mail: zhangdehai@mirslab. cn

ment such as laser radar, microwave radiometer, and atmospheric edge detector. 664 GHz is an important frequency point and also the focus of this paper.

Harmonic mixers based on Schottky diode are applied in solid-state terahertz receivers due to reducing the LO frequency to 1/N of the RF frequency especially when the working frequency raised up to 1THz. Meanwhile, harmonic mixers directly decide the performance of terahertz receivers as a first-level device. Lots of researches on the corresponding design of terahertz mixer and receiver system have been done in recent years.

In Ref. 8, a 640 GHz terahertz receiver channel was designed and mounted on compact scanning sub-millimeter wave imaging radiometer (CoSSIR) to carry out experimental research on the size of ice particle and ice water path. This receiver channel has a noise temperature of 4306K. The ice cloud imager (ICI) is the observation load of Meteorological Operational Second Generation (MetOp-SG) which is the next generation meteorological satellite of ESA. As a precursor, International Sub-Millimeter Airborne Radiometer (ISMAR) was developed to test the retrieval algorithms which carry a receiver channel working at 664 GHz. The 664 GHz receiver channel has a noise temperature of 2 500 K and 2 000 K at horizontal and vertical polarization among 8.4 GHz bandwidth[10-11]. A sub-harmonic mixer operated at 685 GHz integrated with a horn antenna is designed in Ref. 12, which has a double-sideband conversion loss between 13.1 dB to 16 dB using 6 mW LO power. In Ref. 13, a 600 GHz 4^{th}-harmonic mixer was designed based on a discrete anti-parallel Schottky diode which has an SSB conversion loss of 27 dB.

As well known, it is difficult to provide enough LO power (greater than 5mW) to pump the sub-harmonic Terahertz mixer as the RF frequency increases to 670 GHz or even higher. Due to the advantage of the fourth-harmonic mixing method, the LO frequency is only one-quarter of the RF frequency which significantly reduces the complexity and cost of the LO chain.

Aiming at a pre-research of ice clouds observation device, this paper presents the design, fabrication, and test of a fourth-harmonic mixer working at 670 GHz based on Schottky diode. The ideal performance of the Schottky diode utilized is predicted using load-pull mixer architecture based on ideal low-pass-filters. The design and measurement process of the proposed mixer is elaborate in detail. Test result presents the minimum SSB conversion loss is 16.7 dB at 665 GHz. At the RF frequency band of 640 ~700 GHz, the SSB conversion loss is below -22.1 dB.

1 Diode modeling

Schottky diodes have been used to mixer design for many years due to its non-linear current-voltage characteristic[12-17]. The diode configuration of anti-parallel can reduce conversion loss by suppressing the fundamental and some odd mixing products[18]. With the working frequency increases, the anode diameter is up to 0.4 μm and even smaller, leading to current saturation and produce excess noise[19-22]. At the same time, the pad size leads to the parasitic capacitance that impacts working frequency bandwidth, while the spacing distance leads to amplitude and phase imbalance of mixing current.

A quasi-vertical Schottky diode is selected for terahertz mixer design and the component parameters are listed in Table 1. The spacing distance is smaller than one of the tenth wavelength around 670 GHz and will not lead to significant mixing imbalance. We build the precise three dimension model of the diode in HFSS software. As shown in Fig. 1, a lumped port is set for the anode junction, and the integral direction is from epi-layer to buffer layer to represent the diode and its polarity.

Table 1 Relative parameters of the Schottky diode
表1 肖特基二极管相关参数

C_{j0}	R_s	Cut-off frequency	Total capacitance	Pad size
1.5 fF	11	7.2 THz	5 fF	70*30*10 μm

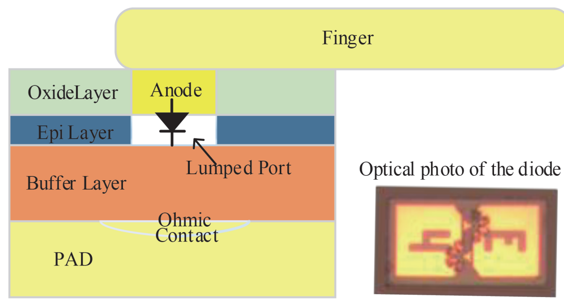

Fig. 1 Structure of anode junction and the lumped port.
图1 肖特基阳极结构和集总端口

2 Mixing theory

The diode configuration in anti-parallel is equaled to co-directional series diodes in theory analysis. Figure 2 shows the basic harmonic mixer circuit based on an anti-parallel Schottky diode[18,23]. The instantaneous currents through diodes can be written as Eq. 1.

$$\begin{cases} i_1 = I_s(e^{-\alpha V} - 1) \\ i_2 = I_s(e^{-\alpha V} - 1) \end{cases} \quad , \tag{1}$$

where I_s is the reversed saturation current; α is the diode slope parameter $(\alpha = \frac{q}{nkT})$, k is the Boltzmann constant, n is the ideality factor, and T is the operating temperature of the diode.

The time-varying conductance, varying with LO signal, is simply the total of the two diode junctions. The conductance of the anti-parallel diode pair can be written as Eq. 2.

$$g = g_1 + g_2 = \frac{d(i_1 + i_2)}{dV} = -\alpha I_s\left(e^{\alpha V_{LO}} + e^{-\alpha V_{LO}}\right)$$
$$= -2\alpha I_s \cosh(\alpha V_{LO} \cos \omega_{LO} t) \quad . \tag{2}$$

The conductance above is an even function which can be expanded by series as follows.

$$g = -2\alpha I_s\left[I_0\alpha V_{LO} + 2I_2\alpha V_{LO}\cos\left(2\omega_{LO}t\right)\right] + \cdots + 2I_{2n}\alpha V_{LO}\cos\left(2n\omega_{LO}t\right) + \cdots] \quad , \quad (3)$$

The total mixing current can be written as:

$$I = i_1 + i_2 = \left(v_{RF}\cos\omega_{RF}t + v_{LO}\cos\omega_{LO}t\right)*g$$
$$= A\cos\omega_{RF}t + B\cos\omega_{LO}t + C\cos 3\omega_{LO}t + D\cos 5\omega_{LO}t + E\cos\left(2\omega_{LO}t + \omega_{RF}t\right) + F\cos\left(2\omega_{LO}t - \omega_{RF}t\right) + G\cos\left(4\omega_{LO}t + \omega_{RF}t\right) + H\cos\left(4\omega_{LO}t - \omega_{RF}t\right) + \cdots + X\cos\left(m\omega_{LO}t + n\omega_{RF}t\right) + \cdots \quad . \quad (4)$$

It can be seen that the mixing current only contains frequency terms where $m + n$ is odd. That's to say the anti-parallel diode can prevent some mixing frequency items which can enhance effectiveness and reduce conversion loss. As to fourth-harmonic mixer, the frequency of the IF (Intermediate Frequency) signal is $f_{IF} = \left|f_{RF} - 4*f_{LO}\right|$.

So, it is necessary to prevent the third harmonic of the LO signal ($f = 3*f_{LO}$) and the second harmonic of the mixing product ($f = \left|2*f_{LO} - f_{RF}\right|$). Filters need to be well-designed to inhibit unnecessary items and output IF signal.

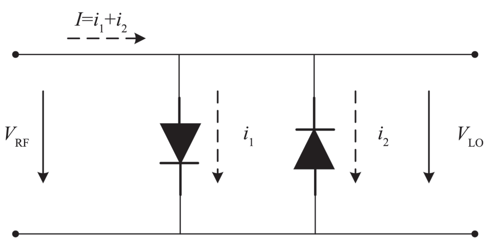

Fig. 2 Anti-parallel diode mixer
图2 反向并联肖特基二极管混频电路示意图

3 Mixer design

Before the overall design of the mixer, optimal conversion loss and the corresponding LO power of the diode pair needs to be known. So, an ideal load-pull mixer circuit is built in ADS according to the topology shown in Fig. 3. The filters shown in Fig. 3 are ideal that has no effects on signal phase. Four ports are set for RF, LO, IF and HF (High Frequency) mixing products. The port impedance of IF and HF is fixed to 100 Ω and the RF/LO impedance is varied.

Using the harmonic balance in DS and setting the conversion loss as optimize goal and tuning RF/LO port impedance, the simulation predicts the minimum SSB conversion loss is 10.3 dB at 667 GHz with 10 mW LO power at 168 GHz.

The proposed Terahertz mixer's architecture and the lower half block of the mixer are shown in Fig. 4. The mixer is designed in hybrid integration based on a dis-

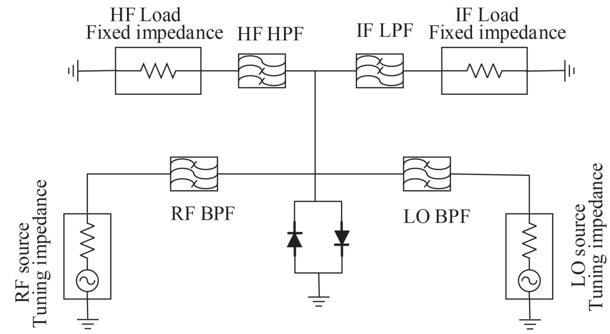

Fig. 3 The ideal mixer circuit topology
图3 理想混频器电路结构

crete quasi-vertical diode which is mounted on a 50 μm thick quartz-glass substrate. The WR-1.5 rectangle waveguide is selected for RF signal from 640 ~700 GHz, while the LO signal is fed via WR5.1. The size of the cavity is accurately designed to suppress the transmission of higher order modes. The size of the cavity is 150 μm× 120 μm (width×height). Then, the IF signal is output through a female SMA connector.

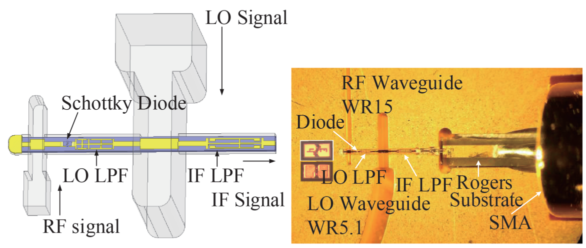

Fig. 4 Proposed terahertz mixer architecture and the assembled mixer block
图4 670 GHz混频器电路结构及其装配实物图

Two low-pass-filters are designed in CMRC architecture, called IF LPF and LO LPF, because of its wide suppression band and low insertion loss in the passband[24]. The CMRC LPF also has the advantage of short length compared with high-low impedance filter, which can reduce the length of the quartz-glass substrate and improve assembly stability.

According to the analysis, the third harmonic of the LO signal (504 GHz), the second harmonic of the mixing product (304~364 GHz), and the RF signal (640~700 GHz) should be inhibited by the LO LPF in order to reduce the conversion loss and LO power.

Three different LO filters are designed and simulated from 0 GHz to 750 GHz. The S21 of the three filters is shown in Fig. 5. Region 1 is the RF frequency band, while region 2 is the frequency range of the second harmonic of the mixing products mentioned above and region3 is the third harmonic of the LO signal. Filter1 is a one-stage CMRC LPF which can inhibit the signal in region 1 in above 20 dB. But, filter 1 has a poor characteristic in region2 in spite of the advantage of the length of 160 μm. As to filter 2, the signal frequency in 310 GHz to 750 GHz can be fully suppressed above 20 dB, which is the LO LPF in the proposed mixer. To filter 3, it has narrow cutoff band compared with filter 1 and filter 2. At the same time, filter 3 can only prevent the signal in region 2 and has a physical length of 530 μm.

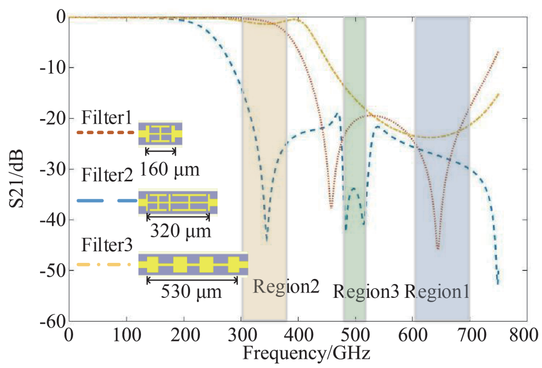

Fig. 5 Comparison of three different LO LPFs
图5 三种不同的本振低通滤波器性能对比图

The overall mixer circuit is constructed in ADS software to simulate the conversion loss, RF/LO return loss and the matching circuit. Based on Harmonic-Balance algorithm, the simulation result exhibits that the SSB conversation loss of the mixer is below 13 dB in the band from 640 GHz to 690 GHz when the LO signal is fixed at 10 mW @ 168 GHz as shown in Fig. 6. The best conversation loss is achieved in 667 GHz of 10. 3 dB. At the best working frequency of 667 GHz, the RF and LO port return loss is -14 dB and -12. 1 dB respectively.

4 Measurement and discussion

For the measurement of conversion loss, the test diagram is depicted in Fig. 7. The test consists of two signal generators (Ceyear 1 442 A, Keysight E8267D), a spectrum analyzer (Keysight PXA N9030B) and a DC source. The RF signal is produced by a signal source extender from VDI which has a multiplier factor of 54. The LO power is generated by a multiplier chain which is composed of a high power 80 GHz source and a 168 GHz doubler.

According to the test diagram, the test bench was

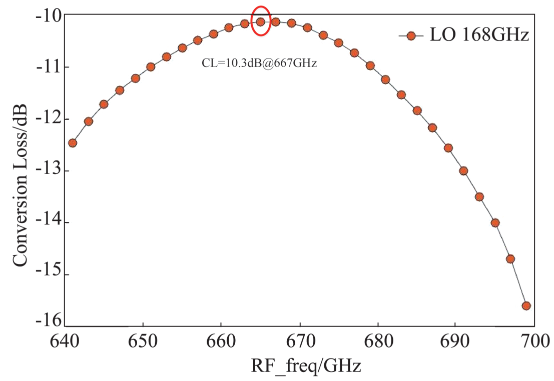

Fig. 6 Simulated mixer performance at 10 mW@168 GHz
图6 在168 GHz的10 mW本振功率驱动下,混频器单边带变频损耗仿真结果

built shown in Fig. 8. The two signal generators are used to drive the LO chain and the 670 GHz signal source. The LO signal is generated by the Ceyear 1 442 A (13. 917 GHz), the W-band multipliers (83. 5 GHz), and the 168 GHz doubler. The output power of the 168 GHz doubler is above 10 mW from 164 GHz to 170 GHz which was calibrated by a PM4 power-meter and can fully drive the mixer. The RF signal is generated by the Keysight E8267D signal generator (11. 851~12. 962 GHz) and the VDI signal extender. The output power of the RF signal is controlled at -17~-22. 1 dBm in the frequency range of 640~700 GHz as the small signal. The IF signal is directly detected by the Keysight PXA N9030B spectrum analyzer with no external IF amplification.

Figure 9 shows the measured conversion loss of the proposed Terahertz mixer. The Terahertz mixer was measured from 640 GHz to 700 GHz at the fixed LO frequency of 168 GHz. It can be observed the measured SSB conversion loss ranges from 16. 7 dB to 22. 1 dB at the RF band. And the minimum CL is 16. 8 dB at 665 GHz shown in Fig. 8. In the whole test process, the LO power signal is controlled at 10 mW of 168 GHz. However, there are two resonance points at the IF frequency of 17 GHz, and the corresponding RF frequency are 655 GHz and 687 GHz. Resonance is caused by assembly because

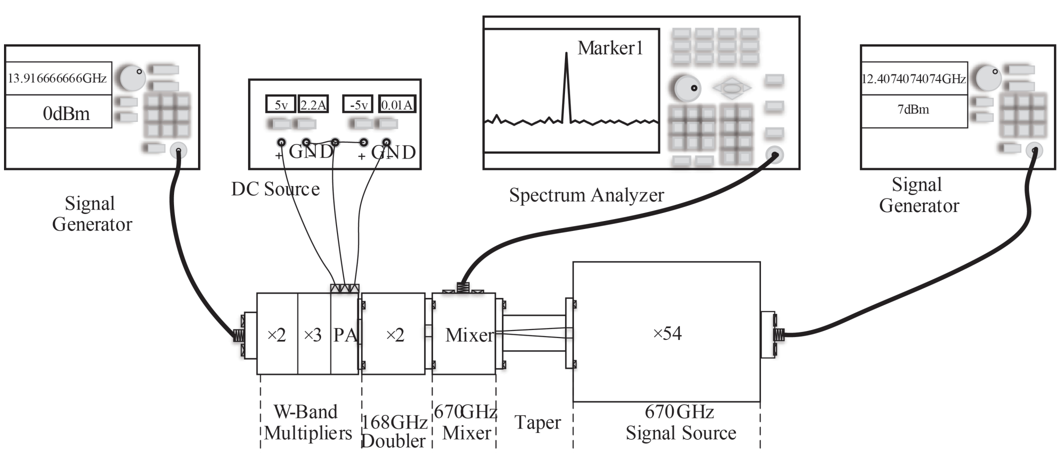

Fig. 7 670 GHz Terahertz mixer measurement platform
图7 670 GHz混频器测试平台

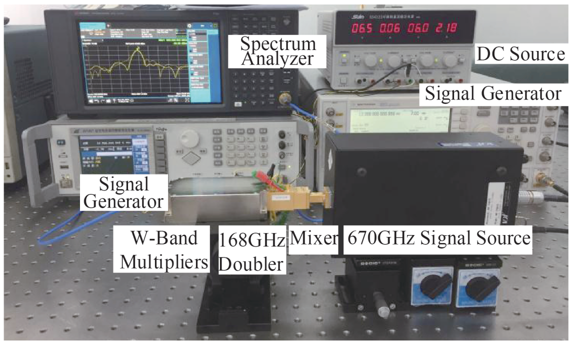

Fig. 8 670 GHz Mixer test bench
图 8 670 GHz混频器测试环境

there is no similar phenomenon in the simulation results. The Rogers substrate will be removed and the quartz glass will be directly bonded to the SMA connector. Table II shows the results of typical harmonic mixers working around 600 GHz and the proposed 4th-harmonic mixer.

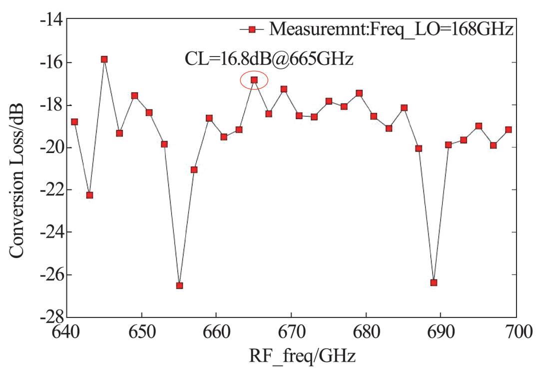

Fig. 9 Measured mixer performance at 17 mW@168 GHz
图 9 在168GHz的17 mW本振功率驱动下,670 GHz混频器单边带变频损耗测试结果

Compared with the simulation results and the actual measured results, there are differences in conversion loss and the required LO power. The LO power increased from 10 mW to 17 mW, which can be explained by two reasons. Firstly, the measured turn-on voltage of one diode junction is 0.98 V, while the ideal barrier height of GaAs is 0.75 V. So the consumption of LO power goes high is reasonable. Secondly, the dislocation of waveguide flanges in different parts and the loss of the waveguide makes the LO power consumption goes high. As to conversion loss of the mixer, the assembly deviation plays an important role. The thickness of the epoxy during the assembly is uncontrollable and varies between 15 μm to 25 μm which is lossy instead of PEC. Additionally, it is necessary to rebuild a new diode model combing DC parameters and high-frequency parameters considering current saturation, skin effect, and plasma resonance.

5 Conclusion

In this paper, a 670 GHz fourth-harmonic mixer was developed using a high-performance Schottky diode for the pre-research of the ice-cloud instrument. Both simulation and measured results are processed to demonstrate the effectiveness of the proposed Terahertz mixer. The mixer is fabricated on a 50 μm thick quartz-glass substrate at suspended configuration. According to the actual test result, the best SSB conversion loss is achieved at 665 GHz of 16.5 dB. The SSB conversion loss is between 16.7 dB to 22.1 dB at the RF range from 640 GHz to 700 GHz at the pump of 17 mW@168 GHz. The property of this proposed Terahertz mixer is very attractive in the application of terahertz receiver around 670 GHz.

Table 2 Results of harmonic mixers around 600 GHz
表 2 600 GHz频率附近谐波混频器性能对比

Ref.	Frequency/GHz	Harmonic times	CL/dB
[12]	660~710	2	13~20(DSB)
[25]	640~680	2	8(DSB)
[13]	600	4	27(SSB)
This work	640~700	4	16.8~22.1(SSB)

Acknowledgment

The authors wish to thank YANG Xiu-Wei and ZHANG XianSheng for the support of the RF frequency source and test equipment.

References

[1] Kangaslahti P, Schlecht E, Jiang J, *et al.* CubeSat scale receivers for measurement of ice in clouds [C]. *Espoo: 2016 14th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment*, 2016: 42-47.
[2] Jasteh D, Hoare E G, Cherniakov M, *et al.* Experimental low-terahertz radar image analysis for automotive terrain sensing [J], *IEEE Geoscience and Remote Sensing Letter*, 2016, **13**(4): 490-494.
[3] WANG C, Lin C X, Chen Q, *et al.* A 10-Gbit/s wireless communication link using 16-QAM modulation in 140-GHz band [J]. *IEEE Transactions on Microwave Theory and Techniques*, 2013, **61**(7): 2737-2746.
[4] Blundell R, Barrett J W, Gibson H, *et al.* Prospects for terahertz radio astronomy from Northern Chile [C]. Massachusetts: *Thirteenth International Symposium on Space Terahertz Technology*, 2002.
[5] Bowman T C, El-Shenawee M, Campbell L K. Terahertz imaging of excised breast tumor tissue on paraffin sections [J]. *IEEE Transactions on Antennas and Propagation*, 2015, **63**(5): 2088-2097.
[6] Buehler S A, C. Jiménez, Evans K F, *et al.* A concept for a satellite mission to measure cloud ice water path, ice particle size, and cloud altitude [J]. *Quarterly Journal of the Royal Meteorological Society*, 2007, **133**(S2): 109-128.
[7] Waliser D E, Li J L F, Woods C P, *et al.* Cloud ice: A climate model challenge with signs and expectations of progress [J]. *Journal of Geophysical Research Atmospheres*, 2009, **114**(8): 0-21.
[8] Blackwell W J, Galbraith C, Hancock T, *et al.* Design and analysis of a hyperspectral microwave receiver subsystem [C]. Munich: *IEEE International Geoscience & Remote Sensing Symposium. IEEE*, 2012: 3435-3438.
[9] Thomas B, Brandt M, Walber A, *et al.* Submillimetre-wave receiver developments for ICI onboard MetOP-SG and ice cloud remote sensing instruments [C]. Munich: *Geoscience & Remote Sensing Symposium. IEEE*, 2012: 1278-1281.
[10] Fox S, Lee C, Rule I, *et al.* ISMAR: A new Submillimeter Airborne Radiometer [C]. Pasadena: *Microwave Radiometry & Remote Sensing of the Environment. IEEE*, 2014: 128-132.
[11] Kangas V, D'addio S, Klein U, *et al.* Ice cloud imager instrument for MetOp second generation [C]. Pasadena: *Microwave Radiometry & Remote Sensing of the Environment. IEEE*, 2014: 228-231.
[12] JIANG Jun, HE Yue, WANG Cheng, *et al.* 0.67 THz sub-harmonic

mixer based on Schottky diode and hammer-head filter [J]. *Journal of Infrared Millimeter Waves*, (蒋均, 何月, 王成, 等. 基于Schottky二极管和Hammer-Head滤波器0.67 THz二次谐波混频器. **红外与毫米波学报**) 2016, **35**(4): 418-424.

[13] Schur J, Ruf M, Schmidt L P. A 4th harmonic schottky diode mixer-facilitated access to THz frequencies [C]. Pasadena: *International Conference on Infrared, Millimeter and Terahertz Waves. IEEE*, 2008: 1-2.

[14] Schlecht E, Siles J V, Lee C, *et al*. Schottky diode based 1.2 THz receivers operating at room-temperature and below for planetary atmospheric sounding [J]. *IEEE Transactions on Terahertz Science and Technology*, 2014, **4**(6): 661-669.

[15] ZHAO Xin, JIANG Chang-Hong, ZHANG De-Hai, *et al*. Design of the 450 GHz sub-harmonic mixer based on Schottky diode [J]. *Journal of infrared and millimeter waves*, (赵鑫, 蒋长宏, 张德海, 等. 基于肖特基二极管的450 GHz二次谐波混频器. **红外与毫米波学报**) 2015, **34**(3): 301-306.

[16] Thomas B, Rea S, Moyna B, *et al*. A 320~360 GHz subharmonically pumped image rejection mixer using planar Schottky diodes [J]. *IEEE Microwave and Wireless Components Letters*, 2009, **19**(2): 101-103.

[17] LIU Ge, ZHANG Bo, ZHANG Li-Sen, *et al.* 0.42 THz subharmonic mixer based on 3D precisely modeled diode [J]. *Journal of infrared and millimeter waves*, (刘戈, 张波, 张立森, 等. 基于二极管3D精确模型的0.42 THz分谐波混频器. **红外与毫米波学报**) 2018, **37**(3): 338-343.

[18] Cohn M, Degenford J E, Newman B A. Harmonic mixing with an antiparallel diode pair [J]. *IEEE Transactions on Microwave Theory and Techniques*, 1975, **23**(8): 667-673.

[19] Hoefle M, Penirschke A, Cojocari O, *et al*. 1/f-noise prediction in millimeter wave detectors based on quasi vertical Schottky diodes [J]. *38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Mainz, 2013: 1-3.

[20] Chen Z N, Chia Y W M. Subharmonic waveguide mixer at 215 GHz utilizing quasivertical Schottky diodes [J]. *Microwave & Optical Technology Letters*, 2015, **27**(2): 93-97.

[21] Cojocari O, Oprea I, Sydlo C, *et al*. Design and characterization of Schottky-structures for THz-Applications [J]. *Frequenz*, 2007, **61**(7-8): 172-177.

[22] Cojocari O, Biber S, Mottet B, *et al*. IF-noise improvement of the GaAs Schottky diodesfor THz-frequency mixer applications [C]. Amsterdam, *12th GAAS symposium*, 2004.

[23] Carlson E R, Schneider M V, Mcmaster T F. Subharmonically pumped millimeter-wave mixers [J]. *IEEE Transactions on Microwave Theory and Techniques*, 1978, **26**(10): 706-715.

[24] Zhang F, Gu J Z, Gu C Y, *et al*. Lowpass filter with in-line beeline CMRC [J]. *Electronics Letters*, 2006, **42**(8): 472.

[25] Subharmonic and harmonic mixers [EB/OL]. (June, 2019) 2019. https://www. radiometer-physics. de/products/mmwave-and-terahertz-products/mixers/mixers-subharmonic-and-harmonic-mixers/high-performance-subharmonic-mixers1.