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A wideband terahertz planar Schottky diode fourth-harmonic mixer with low LO power requirement

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Abstract: A wideband terahertz fourth-harmonic mixer with low local oscillator (LO) power requirement based on anti-parallel planar Schottky diodes is proposed. In order to realize best performances of the mixer, the relations between the parasitic elements of Schottky diodes and the mixer's performances are analyzed. The main parameters of Schottky diodes are optimized to reduce the optimum LO power of the fourth-harmonic mixer. Measured results show that the conversion loss of the proposed mixer based on specialized diodes is 14.2 ~ 20 dB within a wide band from 340 to 490 GHz with optimal LO power of 7 mW, while the noise temperature is 4020~17100 K in this frequency range.

Key words: Fourth-harmonic mixer, low local oscillator power, Schottky diode, Terahertz band, wideband

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基于肖特基二极管的宽带低本振功率太赫兹四次谐波混频器

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摘要：介绍了基于反向并联肖特基二极管的宽带低驱动功率太赫兹四次谐波混频器。详细地分析了二极管寄生参量与混频器性能间的关系。为了降低四次谐波混频器的最佳本振功率，对肖特基二极管的主要参数进行了优化。实际测试结果显示，在 7 mW 的最佳本振功率驱动下，该四次谐波混频器在 340~490 GHz 的宽带内，变频损耗在 14.2~20 dB 之间。同时，该频段内的混频器噪声温度为 4020~17100 K。

关 键 词：四次谐波混频器；低本振功率；肖特基二极管；太赫兹频段；宽带

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Introduction

The unique characteristics of terahertz wave and its application in communication, imaging, and detection have attracted a lot of interests and researches[1-4]. Mixer, as one of the most important components of terahertz systems, directly influences the integral performance of the systems. Subharmonic mixers are widely researched due to its ability to reduce the local oscillator (LO) frequency to half of its radio frequency (RF) frequency[5-11]. However, if the operating frequency keeps increasing, the difficulty of offering LO power will increase, especially for wideband mixers, which require wideband LO sources with enough output power.

Mixers using higher harmonics could be alternatives to solve the aforementioned problem[12-20]. The LO frequency can be further reduced compared with subharmonic mixer. The two main drawbacks of higher harmonic mixers are the worse conversion loss compared with subharmonic mixers and the requirement of higher LO power. For sixth, eighth and even higher harmonic tera-

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hertz mixers, thermal damaging of the diode chip due to excessive LO power needed to realize optimal performance makes them unpractical for system applications[16]. Fourth-harmonic mixer as a compromising option has attracted lots of interest recently[16-20]. The use of fourth harmonics of LO signal leads to the reduction of LO frequency compared with subharmonic mixers, while the required LO power is lower than the mixers using higher harmonics. However, the requirement of high LO power still needs to be considered for the fourth-harmonic mixers with higher operating frequency.

In this paper, a 425 GHz fourth-harmonic mixer with wide operating band and low conversion loss is proposed. The mixer is designed with a combination of 3D EM simulation and harmonic balance simulation. An improved Hammerhead low pass filter, which has wide stopband and good rectangular coefficient[21-23], is applied to realize the wideband mixer. Another purpose of this paper is to solve the high harmonic mixers' problem of requiring high LO power. The relations between the optimal LO power along with other performances of terahertz mixers and the parameters of the Schottky diode are analyzed. Based on these analyses, the primary parameters of diodes for fourth-harmonic mixer such as the anode size, the thickness and doping density of the epitaxial layer are determined to reduce the required LO power. The mixer diodes applied in this paper are designed by the cooperation of CETC-13 (China Electronics Technology Group Corporation, Institute No. 13) and UESTC (University of Electronic Science and Technology of China), manufactured by CETC-13. With the specialized Schottky diodes, the integral mixer circuit was simulated and fabricated. According to the authors' knowledge, the fourth-harmonic mixer proposed in this paper features the lowest optimal LO power compared with previous researches in the same operating frequency band.

1 Circuit Design

1.1 Configuration of the fourth-harmonic mixer

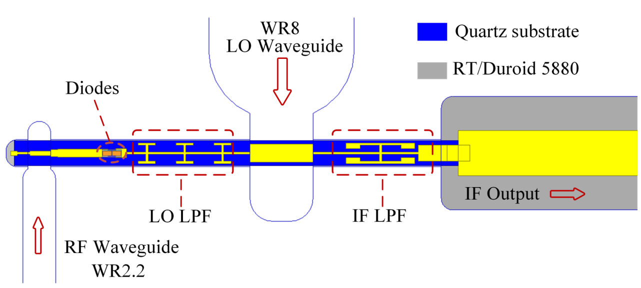

Fig. 1 Configuration of the proposed fourth-harmonic mixer
图1 四次谐波混频器整体结构图

The configuration of the fourth-harmonic mixer circuit, shown in Fig. 1, includes an anti-paralleled of flip-chip Schottky diodes mounted on quartz-based microstrip circuit, RF and LO waveguide-to- microstrip transitions, intermediate-frequency (IF) and LO low-pass filters (LPF), as well as RF and LO matching networks. The dimensions of the suspended microstrip and the substrate are optimized to ensure that the RF and LO signals propagate on the quasi-TEM mode, and that no unwanted transmission mode coupling occurs[24]. The LO and RF waveguide-to-microstrip transitions are optimized for broadband operations by using wide E-probes and waveguides with reduced height. The LO and IF low pass filters using hammerhead structure are applied to isolate the LO, RF, and IF signals, so that the good performances of the mixer could be guaranteed.

The suspended microstrip circuit is developed using quartz substrate with thickness of 50 μm, width of 220 μm and dielectric constant of 3.78. One end of suspended microstrip circuit is connected to a microstrip line based on Rogers 5880 substrate by bondwire or silver epoxy to output IF signal, so that a robust structure of the mixer can be obtained.

1.2 Modeling of the Schottky diode at THz band

For terahertz mixers, the Schottky diode is the key component to realize frequency conversion with its nonlinear characteristics. Higher operating frequency will limit the diode performances due to the parasitic effect. For millimeter wave and terahertz circuits, the influences brought by the diode parasitic will result in power loss and affect the input power coupling to the nonlinear diode junction, and the integral performances of the mixer circuit will be affected. Therefore, a modeling method combining the simulation of both electric field and circuit is essential to solve the problem.

The cross section view and parasitic parameters of the typical planar Schottky diode are shown in Fig. 2. The parasitic parameters will bring the degradation to the diode performance. The parasitic resistance, also called as series resistance R_S, mainly consists of four parts: the epitaxial layer resistance R_{epi}, the buffer region resistance R_{buffer}, the ohmic contact resistance R_{ohmic}, and the air bridge resistance R_{finger}[25]. The parasitic capacitance is comprised of two main parts, finger capacitance (C_f) and pad capacitance (C_{pp}). C_{pp1} and C_{pp2} represent electrical coupling between contact pads through air and semi-insulating GaAs substrate. For finger capacitance, the two main parts include the coupling between finger and buffer layer (C_{fb}) and between finger and pad (C_{fp}).

At submillimeter wave and terahertz bands, the parasitic effect of the planar Schottky diode cannot be ignored. Therefore, the model of the Schottky diode is

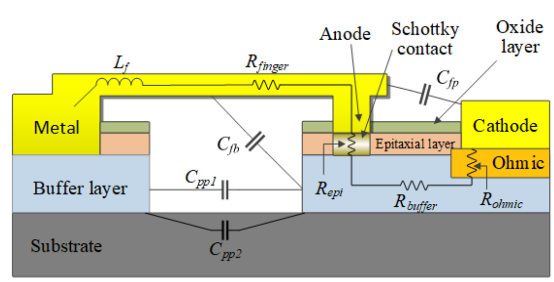

Fig. 2 Cross section view and parasitic parameters of the planar Schottky diode
图 2 平面肖特基二极管截面图及寄生参数

built, as shown in Fig. 3. To design the mixer, the 3D EM simulations are used to obtain the S parameters of the chip package, which present the structure and parasitic effects of the diode. These S parameters are imported to the nonlinear circuit simulating software (Agilent's ADS), while the external matching network of the fourth-harmonic mixer is optimized to realize the best performances.

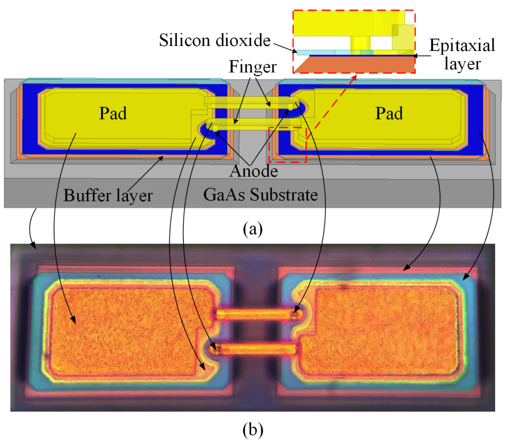

Fig. 3 (a) The 3D EM model of the planar Schottky diode (b) The picture of the Schottky diode applied manufactured by CETC-13
图 3 (a)平面肖特基二极管的三维电磁模型;(b)中电十三所加工的平面肖特基二极管的照片

1.3 Methodology of reducing LO power for fourth-harmonic mixer based on optimized Schottky diodes

As mentioned above, the requirement of LO power is an important consideration among other performances. And the fourth-harmonic mixers need more LO power according to the previous researches. To analyze the relations between the parameters of the Schottky diode and the required LO power along with other performances, the equivalent circuit of the Schottky diode is built and shown in Fig. 4. The equivalent circuit is modeled with a junction resistor $R_j(V_j)$, a junction capacitor $C_j(V_j)$, and a series resistor $R_S(V_j)$.

From the equivalent circuit in Fig. 4, the relations between the junction resistance R_j, the junction capacitance C_j, and the series resistance R_S can be obtained. The LO power dissipating on series resistance will be influenced by R_S and C_j. With fixed diode voltage V_d between the anode and cathode, the bias voltage of the junction V_j increases with the decrease of R_S and C_j, which is essential to reduce the LO power of mixers.

There are two ways to reduce the required LO power, either increasing the coupling efficiency between the source and the diode or reducing the power needed in the diode itself[26]. Therefore, several methods should be applied.

1. Minimize the parasitic elements as much as possible. The parasitic elements, especially the series resistance, contribute a lot to the dissipation of the LO power before it reaches the nonlinear junction resistance.

2. Reduce the junction capacitance adequately. Firstly, the junction capacitance contributes to the LO power dissipation. Apart from that, reducing the junction capacitance could increase the coupling efficiency between the external circuit and the diode itself according the previous researches[26], and the LO power could be further reduced in this way.

3. Optimize the external matching network of the mixer diode. The losses of the external circuit and the matching network also greatly influence the LO power coupling to the diode junction.

Apart from the optimal LO power level, other performances of the Schottky diode and the fourth-harmonic mixer also need to be emphasized. For example, the reduction of the series resistance and junction capacitance could increase the cut off frequency.

The most important performances for the mixer are the conversion loss and noise temperature. Besides the matching circuit, parameters of the Schottky diodes also decide these performances. At terahertz band, the parasitic capacitances also contribute to the degradation of the noise and conversion loss and should be controlled as well[27]. For noise of the Schottky diode, several researches[28-29] have been done, revealing that increasing the doping density will mitigate the hot-electron noise, which plays an important role in the noise of diode at terahertz band. Therefore, high doping density should be applied to realize the low noise mixer.

Based on the analyses above, reducing the parasitic elements and decreasing junction capacitance of the Schottky diode adequately could reduce LO power and improve the integral performances. In this paper, the Schottky diodes applied for the fourth-harmonic mixers with low LO power requirement are designed with following steps.

1. Choose high doping density for epitaxial layer. According to the analyses, improving the doping density of the epitaxial layer is essential due to the importance to reduce the noise and series resistance. In this paper, the doping density of 5×10^{17} cm^{-3} is applied.

2. Optimize the structure of the Schottky diode. The thickness of the epitaxial layer needs to be reduced adequately to minimize the series while the parasitic capacitance can be reduced by decreasing pad area, in-

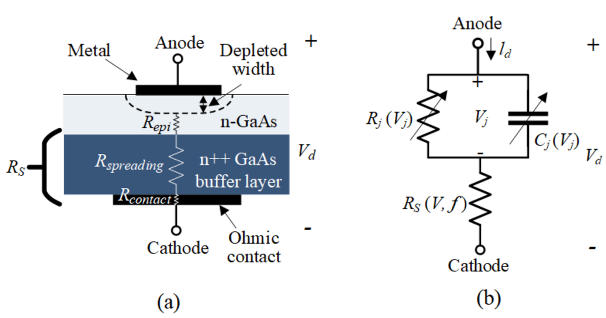

Fig. 4 (a) Simplified model of the diode junction (b) Equivalent circuit of the Schottky diode
图 4 (a)二极管肖特基结简化模型;(b)肖特基二极管等效电路

creasing pad separation, decreasing substrate dielectric constant and substrate thickness. In Fig 5, the main dimensions of the applied Schottky diodes are illustrated. The thickness of the epitaxial layer is 0.2 μm, while the thickness of the buffer layer is 3 μm.

Due to the wet etching process, the angle between the GaAs substrate and the slanted side wall is 55° [30]. The width of the surface channel is 16 μm. As for the GaAs substrate of the diode chip, its thickness is 25 μm.

Considering the fabrication processes of the mixer based on flip chip diodes, in which the diode chip is welded to the microstrip with silver epoxy, the pads of the Schottky diodes need to be large enough. In this design, the pad dimensions are 45 μm × 27 μm.

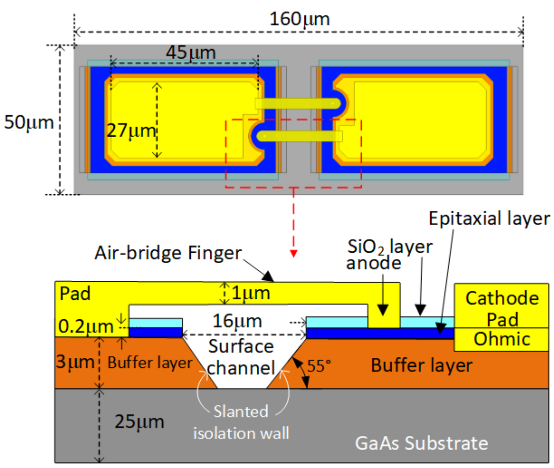

Fig. 5 Dimensions of the Schottky diode applied in the proposed fourth-harmonic mixer
图 5 应用于本文四次谐波混频器的肖特基二极管的相关结构尺寸

3. Decide the anode size. Based on the doping density and other parameters of the diode, the anode size should be optimized to realize good performances of the mixer, including low conversion loss and low optimal LO power. Reducing the size of the anode will lead to the decrease of the junction capacitance but will also increase the series resistance. The simulation of the ideal fourth-harmonic mixer is developed using ideal diodes without considering the diode packages. The conversion loss and optimum LO power with different zero junction capacitance (C_{j0}) of the mixer diode are shown in Fig. 6. Best performances are achieved with C_{j0} around 1 fF. Based on other parameters of the diodes, an optimum anode diameter of 0.7 μm with corresponding C_{j0} of 1.1 fF is obtained.

The Schottky diodes specially designed for the fourth-harmonic mixer in this paper are manufactured by CETC-13. Its overall dimensions are 160 μm × 50 μm × 30 μm. The mixer diodes are with following parameters: saturation current I_{sat} = 35 fA, series resistance R_S = 20Ω, ideality factor η = 1.3, zero voltage junction capacitance C_{j0} = 1.1 fF, and built-in potential V_{bi} = 0.73 V.

Based on the specialized Schottky diodes, the

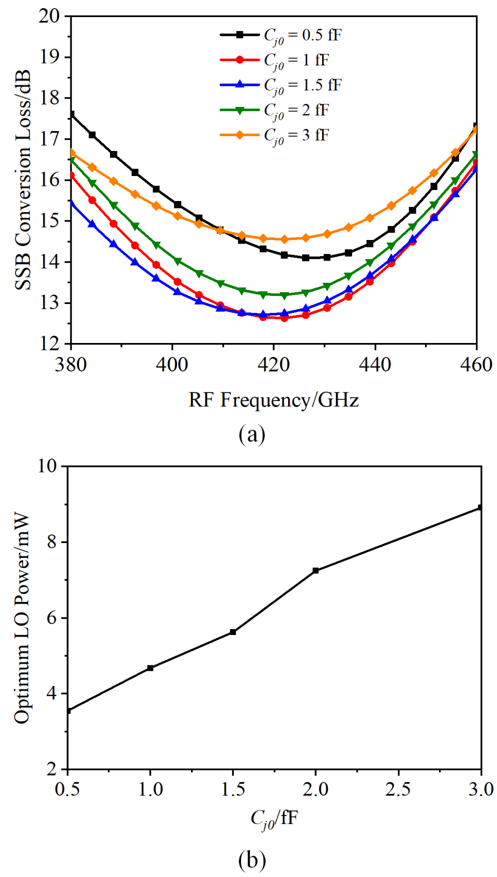

Fig 6 (a) Optimum conversion loss of the mixer with different C_{j0}, (b) Optimum LO power of the mixer with different C_{j0}
图 6 (a)不同 C_{j0} 对应混频器的最优变频损耗;(b)不同 C_{j0} 时混频器的最优本振功率

matching network of the fourth-harmonic mixer is further optimized in ADS with S parameters of each part of the mixer, and the final performances of the fourth-harmonic mixer could be obtained with harmonic balance simulation in ADS.

1.4 Wide stopband terahertz low pass filter using hammerhead configuration

The main function of the LO low-pass filter (LPF) is to isolate the RF signal and the unused harmonics from the LO port, while directing the LO signal towards the diodes with lower loss. In this paper, the LPF uses the hammerhead configuration, which is more compact compared with a stepped- impedance LPF with same passband and stopband. The comparison between the proposed hammerhead LPF and a stepped-impedance LPF with similar passband is shown in Fig. 7. Simulated results show that insertion loss of the proposed Hammerhead LPF is higher than 20 dB from 182 to 500 GHz, which validates the good isolation for RF signal (325 ~ 400 GHz) and unused harmonic signals generated at the mixer diodes (second harmonic signal with frequency from 162 GHz to 250 GHz). The insertion loss of the LO filter is lower than 0.4 dB from DC to 130 GHz, which enables the IF and LO signal passing with low loss. Compared with the stepped-impedance LPF with similar pass-

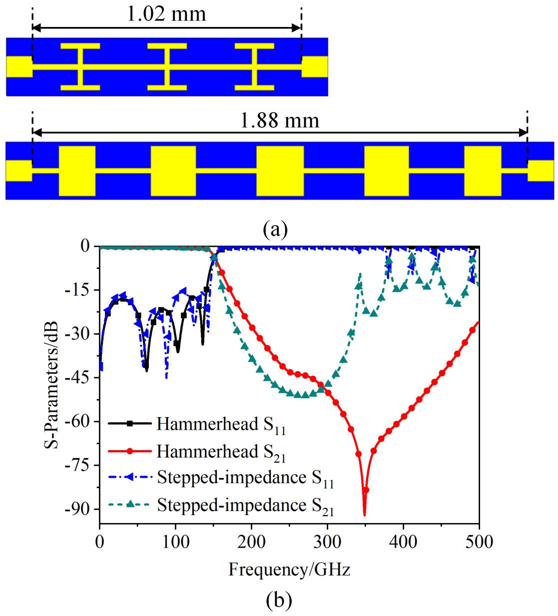

Fig. 7 (a) Topology and simulation results of the wide stop-band and high rejection LO low pass filter
图 7 (a)宽阻带高抑制度本振低通滤波器结构图和仿真结果

band, the proposed hammerhead LPF exhibits much wider stopband and more compact size. The good performances of the LO filter also contribute to the reduction of LO power.

1.5 Overall circuit simulation

The overall simulation of the fourth-harmonic mixer is developed with a combination of 3D electromagnetic (EM) simulations and harmonic balance simulation. The 3D EM simulations of the different parts of the mixer circuit including the RF and LO waveguide-to-microstrip transitions, diode cells, low-pass filters were developed separately using High Frequency Software Simulator (HFSS) and exported as S-parameter Touchstone files into ADS. The simulated performances with different LO power are shown in Fig. 8. Simulated results show that, the best performances are obtained with an optimal LO power of 7 mW. The single sideband (SSB) conversion loss is better than 20 dB from 325 to 500 GHz with fixed IF frequency of 1 GHz and the simulated noise temperature is 3 060~12 800 K within this frequency band.

2 Measurement results and analysis

The Schottky diodes specially designed for the proposed fourth-harmonic mixer were manufactured in CETC-13 and the mixer circuit was fabricated and measured in UESTC. The mixer circuit mounting in the split block is shown in Fig. 9. It's manufactured using 50 μm-thick quartz substrate, while the anti-paralleled Schottky diodes were welded to the circuit with silver epoxy. The overall dimensions of the quartz substrate are 3.5 mm × 0.22 mm × 0.05 mm. The whole circuit is suspended in an enclosed channel crossing the RF and LO waveguides, which are WR2.2 (0.508 mm × 0.254 mm) and WR8 (2.032 mm × 1.016 mm), respectively.

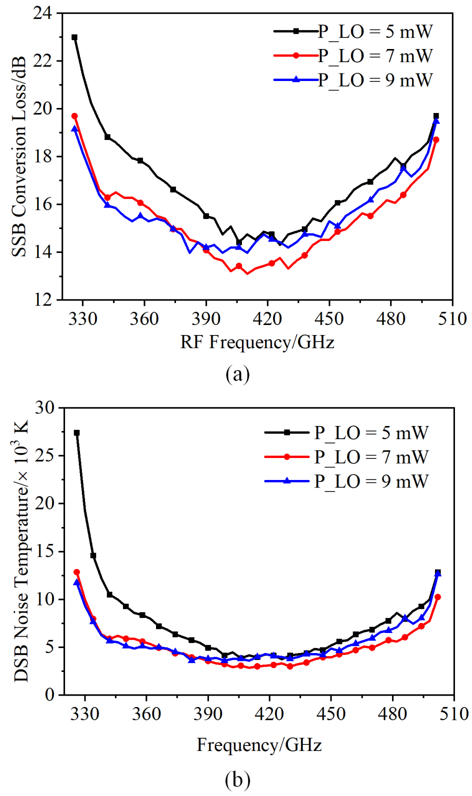

Fig. 8 Simulated performances of the proposed fourth-harmonic mixer with different LO power (a) SSB conversion loss, (a) DSB noise temperature
图 8 不同本振功率下四次谐波混频器的仿真结果(a)单边带变频损耗;(b)双边带噪声温度

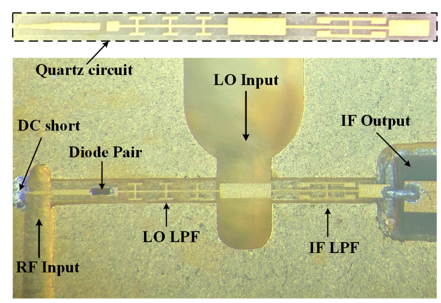

Fig. 9 Inside photograph of the fourth-harmonic mixer
图 9 四次谐波混频器内部照片

The test setup for SSB conversion loss is shown in Fig. 10. The RF signal was provided with a ×12 multiplier chain and the power of RF signal should be controlled at a low level (0.1 mW in this paper) to ensure the mixer working in its linear range. Meanwhile, the LO signal was generated by a ×6 multiplier chain with operating frequency from 81 to 125 GHz. As for the measurement for noise temperature of the fourth-harmonic mixer, the Y factor method and gain procedure illustrated in Ref. [31] are applied. The test setup for noise temperature is shown in Fig. 11.

According to the measured results, the best performances of the fourth-harmonic mixer are achieved with LO power of 7 mW. Fig. 12 shows the comparison be-

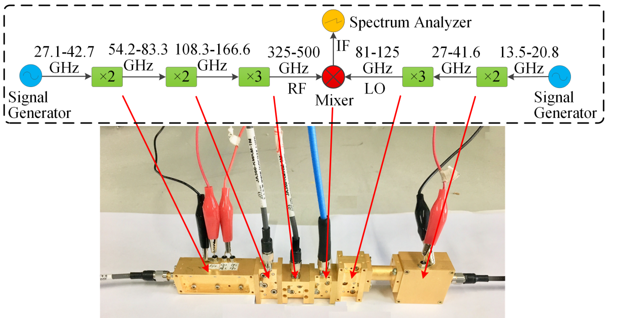

Fig. 10 Test setup for conversion loss of the fourth-harmonic mixer
图 10 四次谐波混频器的变频损耗测试平台

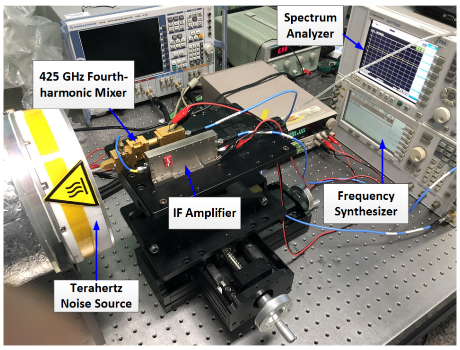

Fig. 11 Test setup for noise temperature of the fourth-harmonic mixer
图 11 四次谐波混频器噪声温度测试平台

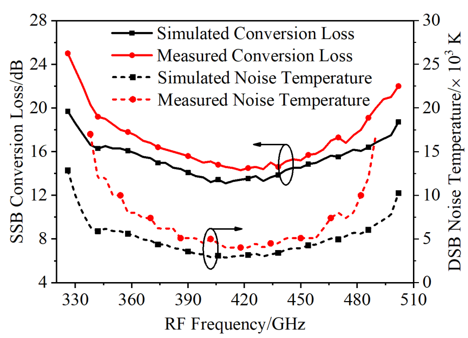

Fig. 12 Comparison between simulated conversion loss and measured results of the proposed mixer with fixed IF frequency of 1 GHz and optimum LO power of 7 mW
图 12 在 1GHz 固定中频和 7 mW 最优本振功率下，混频器仿真和测试的变频损耗的对比

tween the simulated and measured performances with LO power of 7 mW and fixed IF frequency of 1 GHz. The SSB conversion loss of the fourth-harmonic mixer is 14.2 ~ 20 dB within the frequency band from 340 to 490 GHz, while the noise temperature is 4020 ~ 17100 K in this frequency range. The best performances of the mixer are realized when the RF is 418 GHz, with conversion loss of 14.2 dB and noise temperature of 4020 K. Good agreements are achieved between the simulated and measured results. The slight difference is brought by inconsistency between the calculated parameters applied in simulation (such as series resistances, junction capacitance) and the actual ones. Inaccurate assembly process could also lead to the differences between the simulated and measured results.

The comparisons between the performances of the proposed and previously reported fourth-harmonic mixers considering both conversion loss and optimal LO power are shown in Table I. It can be concluded that the proposed mixer achieves better conversion loss over a wide frequency band with lower LO pump power. In this paper, the fourth-harmonic mixer is developed based on the optimized Schottky diodes and the best LO power is lower compared with that in Ref. [18-19]. High doping density is applied and several parameters of the Schottky diodes, such as anode size, are optimized to realize low optimal LO power. The performances of the mixer have validated the proposed methods to design the mixer with low LO power requirement.

Table1 Summary of the performances of the reported fourth-harmonic mixer
表 1 已报道的四次谐波混频器的性能总结

Ref.	RF freq. / GHz	CL /dB	NT (DSB) /K	OLOP /mW
[17]	600	27 (SSB)	NI	20
[18]	430 ~ 480	14 ~ 20 (DSB)	7900 ~ 20000	10
[19]	325~ 500	15 ~ 22 (SSB)	NI	20
This work	**340~ 490**	**14.2~20 (SSB)**	**4020 ~ 17100**	**7**

CL: Conversion Loss; NT: Noise temperature; OLOP: Optimal LO power; DSB: Double Sideband; SSB: Single Sideband. NI: Not Indicated.

Schottky diodes with small anode size and highly doped epitaxial layer are utilized to realize the good performances of terahertz mixers. These characteristics lead to the low power capacity of the mixer diodes. Therefore, mixers using high harmonics are usually restricted by high optimal LO power, which could damage the diodes. The method of reducing LO power proposed in this paper can resolve the conflict between the need of excessive LO power for high harmonic terahertz mixers and the low power capacity of the mixer diode. It will contribute to the development of terahertz systems using high harmonic mixers in the future.

3 Conclusion

This paper presents the development of a terahertz fourth-harmonic mixer with wide operating band, low conversion loss and low LO power requirement. The 3D model of the flip chip Schottky diode was built and a combination of EM simulation and nonlinear harmonic balanced simulation were applied to design the mixer. Meanwhile, the methods of realizing high harmonic mixer with good performances and less LO power are introduced. With optimum LO power of 7 mW, the measured conversion loss of the proposed fourth-harmonic mixer is 14.2 ~ 20 dB from 340 to 490 GHz, while the measured noise temperature is 4 020~17 100 K in this frequency range. The fourth-harmonic mixer proposed in this paper features lower LO power requirement compared with previous research. It can be applied in terahertz systems to simplify the system with lower LO frequency. The methods of reducing the required LO power can be utilized to improve the performances of mixers using even higher harmonics in the future.

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