Design of 220GHz harmonic mixer

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Abstract. 220GHz is the frequency of atmospheric window. The mixer working in this frequency band has a very important application in terahertz communication detection and other fields. This paper introduces a mixer design based on planar Schottky barrier diode. Based on the reverse parallel diode fabricated by the process platform of the 13th Research Institute of China Electronics Technology Group Corporation. The schematic layout of the mixer is simulated and optimized by the joint design of ADS and HFSS and other electromagnetic simulation software. Finally, The frequency conversion loss is less than 9 in the range of 200 to 240 RF frequencies.

1. Introduction
Terahertz wave (0.1THz-10THz) is a hot research direction in recent years. It has the characteristics of strong directivity, wide bandwidth, strong penetration, high resolution, large information capacity, higher angular resolution, higher brightness and temperature resolution. [1] Therefore, it is used in atmospheric exploration [2], earth observation and satellite-to-Earth communication systems, medical imaging. Telemetry and remote sensing, military confidential communications and other aspects have very good prospects. Super heterodyne receivers in terahertz band have very high sensitivity and frequency resolution, in which mixer plays an important role. It converts radio frequency signal to intermediate frequency signal. The sensitivity of receiver is largely determined by mixer.

The mixer needs the local oscillator at the same frequency if it wants to be converted. However, due to the high frequency of terahertz wave, it is difficult to fabricate local oscillator in the same frequency band. Therefore, the reverse parallel diode is used for harmonic mixing. [3] The frequency required by the local oscillator is half that of the radio frequency signal, which reduces the difficulty of the local oscillator requirement.

At present, terahertz harmonic mixer has been studied abroad for many years, while the domestic research on this aspect is relatively late, but in recent years there have been some related articles published.

In 2012, XiaoFan Yang of University of Electronic Science and Technology and others designed a 380GHz sub-harmonic mixer [4], which uses a planar Schottky barrier diode made by Rutherford Laboratory. The physical model of the diode is studied systematically, and the performance parameters of the diode in the frequency band are extracted. A system-level simulation method is proposed, which adds optimized variables and greatly simplifies the circuit structure. The test results show that the frequency conversion loss of the mixer is less than 10 dB in the range of 2.3 GHz to 3.5 GHz of IF output. The optimum local oscillator power is 4 mw. At the same time, the feasibility of system-level simulation is also demonstrated.
In 2016, Zhenyu Feng of University of Electronic Science and Technology and others designed a 440 GHz sub-harmonic mixer [5]. The simulation results show that the frequency loss of the mixer is less than 10 dB in 420-460 GHz driven by 3.3 mw local oscillator power.

In this paper, a Schottky reverse parallel diode pair developed by the Thirteenth Institute of Electrical Sciences of China is adopted. The circuit form is a suspended microstrip line structure. RF and local oscillator signals are input through a rectangular waveguide, and intermediate frequency is output through a SMA joint in the form of microstrip.

2. Principle
Mixing Principle of Reverse Parallel Diode Pairs

As can be seen from Figure 1

\[ i_1 = i_e (e^{aV} - 1) \] (1)
\[ i_2 = -i_e (e^{-aV} - 1) \] (2)

therefore
\[ i_1 + i_2 = i_e (e^{aV} - e^{-aV}) = 2i_e \sinh(aV) \] (3)
\[ V = V_{LO} \cos \omega_{LO} t \] (4)
\[ g = \frac{d_i}{d_v} = 2a_i \cosh aV_{LO} \cos \omega_{LO} t \] (5)

Therefore, Fourier expansion of the above formula (5) yields
\[ g = 2a_i \sinh(aV_{LO}) + 2i_2(aV_{LO}) \cos 2\omega_{LO} t + 2i_4(aV_{LO}) \cos 4\omega_{LO} t + \cdots (6) \]

Under the excitation of the local oscillator signal and the voltage \( i = gV_s = vs \) of the radio frequency signal, it is obtained.
\[ 2a_i \sinh aV_{LO} \cos 2\omega_{LO} t + 2i_2(aV_{LO}) \cos 2\omega_{LO} t + 2i_4(aV_{LO}) \cos 4\omega_{LO} t + \cdots \]

As can be seen from the above formula, the reverse parallel diode current appears \( (2\omega_{LO} \pm \omega_s) \), \( (4\omega_{LO} \pm \omega_s) \). With equal components, the local oscillator only has even harmonics, the odd harmonics are suppressed [6], the useless frequency of output in the circuit decreases, the proportion of useful frequency increases, and the net frequency conversion loss of the nonlinear conductance of the mixer is reduced, thus the frequency conversion loss is reduced.

3. Design of Second Harmonic Mixer

3.1. Design Scheme
In this paper, the design method of mixer is based on the overall performance of mixer. The characteristic parameters of transmission line are extracted by HFSS, and replaced by ideal transmission line in ADS. The passive structure outside the transmission line is simulated and exported into ADS by HFSS. Then the whole simulation and optimization are carried out in ADS, and the ideal results are obtained. Then the whole model is simulated in HFSS, and then the SNP file is exported to ADS to check the results of harmonic simulation. If it does not meet the standard, it needs to be adjusted until the target is reached. Attention should be paid to the de-embedding settings when extracting the passive structure, so as to prevent the fading modes (which will decay with distance) caused by discontinuities from affecting the results.

The selected RF waveguide model is WR-10, the local oscillator waveguide model is WR-04.3, the circuit base material is quartz substrate, and the principle of selecting the size of the shielding cavity is not to transmit high-order modes. In order to reduce the loss, the thickness of quartz substrate is selected as 50um. Verify that the transmission of high-order mode can be simulated in HFSS. The port is set to multiple modes, and then look at the S_{21} of high-order mode. If the value of high-order mode S_{21} is very small, it can be considered that high-order mode is not transmitted.

Firstly, a reasonable topology structure is needed to optimize the mixer as a whole. According to the overall structure adopted in reference paper [7], as shown in Figure 2 below, the high and low impedance filter between the secondary tube and the local oscillator signal acts as a local oscillator signal to block the radio frequency signal, and a low-pass filter can be used because the local oscillator signal frequency is less than half of the radio frequency signal frequency. Band-stop filters can also be used to make band-stop filters that can only block radio frequency signals. Band-stop filters can be achieved by shunt half of the radio frequency wavelength open circuit. In this paper, the high and low impedance low-pass filters are used. The output position of IF signal is also a low-pass filter with high and low impedance. Its function is to prevent IF signal from local oscillator signal. The grounding scheme adopted in this paper is to make the quartz substrate buckle on the cavity, and the grounding part is directly connected with the cavity. On the one hand, quartz substrates can be fixed, on the other hand, because the band line is directly connected with the cavity, it can be used as the ground of intermediate frequency signal and local oscillator signal.

The overall structure can be determined and optimized in ADS according to the above comprehensive design method. The optimization objectives are the variable loss of fixed local oscillator time and fixed intermediate frequency value, standing wave at radio frequency, standing wave at local oscillator, the optimized variable is the length from radio frequency to ground, the length of diode terminals, local oscillator filters line length and IF filter line length. Through optimization, it is found that it is not easy to make both RF standing wave and local oscillator standing wave have good results at the same time. Therefore, the structure of impedance transformation is set up at the local oscillator waveguide, which increases the optimization of waveguide length at the local oscillator. Changing the length of the position has little effect on the standing wave and frequency loss, but it can improve the standing wave at the local oscillator. In the optimization process, the standing wave and insertion loss can be optimized first, and then the length of the transformation structure at the local oscillator waveguide can be adjusted to optimize the standing wave at the local oscillator.
Finally, because the IF output of quartz substrate is buckled on the microstrip line, it is necessary to simulate the IF output position to see if it will affect the performance of the mixer, as shown in Figure 3, the model diagram of the IF output position and the simulation results. It can be seen that the impact is very small, so such a design can be carried out.

3.2. Optimized results
In the simulation, in order to make the simulation more suitable to the actual results. The size of some Rs is increased. In HFSS simulation, RF local oscillator IF diodes are set as wave ports, waveguide ports are set up as integral lines and $Z_{in}$ is selected. The simulation results show that the SNP file package is placed in ADS (as shown in Figure 3 below) to see the results.
Figures 4 and 5 below show the simulation results.

Fixed Local Oscillator Scanning Radio Frequency

Fig 4. ADS simulate

Fig 5 a. CL

Fig 5 b. S11_lo
Fig. 5 is the frequency conversion loss of fixed local oscillator scanning RF. It can be seen that the frequency conversion loss is flat from 200 GHz to 240 GHz, and the loss value is less than 9 dB. From Fig. 5B and c, it can also be seen that the local oscillator standing wave and the radio frequency standing wave meet the requirements. From 210 GHz to 228 GHz, the local oscillator standing wave is less than $-15$. Basically, there was no change near $-15$ dB. As can be seen from Fig. 6, when the RF is fixed, the local oscillator standing wave is below $-10$ in the range of 5 GHz. This is to prevent the local oscillator standing wave from deviating due to assembly errors, so there are some margins left in the simulation.

3.3. Assembly Error Analysis
The position change of diode assembly may cause the effect of mixer to deteriorate, so some simulation
validation is carried out to verify the effect of diode assembly error. Figure 7 below is the result of the left offset of the diode by 20um. Compared with Fig. 5, it can be seen that the insertion loss has little effect and is within a reasonable range. In addition, in order to make quartz substrates easy to fabricate, it should not be too long, too long and easy to break, it is necessary to re-optimize the simulation and get as short as possible.

![Fig7 a. no deviation](image1.png)

![Fig7 b. 20um deviation](image2.png)

4. Summary
A 220 GHz mixer is designed in this paper. Through simulation and optimization, the frequency conversion loss is less than 9dB from 200 GHz to 240GHz. The RF standing wave and local oscillator standing wave also meet the requirements.

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