420 GHz subharmonic mixer based on heterogeneous integrated Schottky diode

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Abstract: This paper describes 420 GHz subharmonic mixer based on heterogeneous integrated schottky diode designed by University of Electronic Science and Technology of China (UESTC) and fabricated by China Electronics Technology Group Corporation-13 (CETC-13). The whole circuit including schottky diodes is integrated directly on the 50 μm quartz instead of the traditional 12 μm GaAs substrate thus the circuit is much easier to manufacture and the cost is much cheaper. The 3D model of schottky diode is built up in the HFSS to extract the parasitic parameters introduced by the diode package when the operating frequency is extremely high. Source-pull and load-pull methods are used to get the optimum RF, LO and IF embedding impedance in the ADS. Measured results show that the minimum conversion loss is 10 dB at 419 GHz and 422 GHz, SSB conversion loss is less than 14.7 dB from 400 GHz to 440 GHz when the LO power is 5.2 dBm at 210 GHz.

Keywords: subharmonic mixer, heterogeneous integrated, schottky diode, source/load pull, parasitic parameters, conversion loss

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

References


1 Introduction

Terahertz wave (300 GHz to 10 THz) lies between microwave and visible light [1] which is the last developed electromagnetic wave. The special position in the electromagnetic spectrum enables terahertz wave to have the merits of both microwave and light wave. The characteristics of higher frequency and shorter wavelength compared with microwave determine it has stronger beam directionality, higher resolution, larger information capacity and smaller electrical size [2]. The characteristics of stronger penetration compared with light waves allows terahertz wave to be applied to rain and fog weather, smoke-filled battlefield and other extreme conditions [3]. Terahertz wave has lower photon energy [4] thus it can be applied to living organisms tissue nondestructive testing. Therefore, terahertz technology has great prospects in application of precision guided weapon, broadband communications, object imaging, environmental monitoring, medical diagnosis and other fields [5].

Radiometers [6] are one kind of passive receiver that can detect and measure the electromagnetic radiation of an object in a certain frequency band. The electromagnetic radiation signal emitted by the observed object is similar to noise and is actually rather weak which requires high performance of the radiometer. Lack of front-end low noise amplifiers makes subharmonic mixers the first stage of the receiver [7] in the terahertz band. Schottky based subharmonic mixer [8] can downconvert the RF input signal to IF output signal preserving the signal phase and amplitude information through intermodulation with LO input signal and only require half the frequency of the fundamental mixer thus lower the difficulty to design efficient high frequency pumping multiplier chain.

Circuit topology can also affect the mixer performance to a large extent which needs to be considered carefully. Hybrid circuit implementation (discrete diode mounted on the substrate manually) in the reference [9, 10, 11] often used in the lower terahertz band and the diodes need to be manually mounted on the circuit which degrades circuit repeatability and stability. GaAs monolithic integrated circuit in the reference [12, 13, 14] is much complicated and expensive. Heterogeneous integrated circuits in this paper replace the GaAs substrate with quartz maintaining similar performance at the same time.

2 Diode modeling

In the terahertz band, diode size can no longer be ignored compared with the operating wavelength, significant parasitic parameters will be introduced due to diode package [15]. 3D model of the schottky diode [16] is established in the HFSS depicted in Fig. 1 to simulate electromagnetic environment and then the simulation results are exported in SNP items to ADS to predict the optimum embedding impedance. Fig. 2 shows the cross sectional view of the diode. The signal passed through the anode to the epi-layer where the nonlinear effects are generated and then the electromagnetic waves pass through the buffer layer to the cathode. The geometrical structure-based electrical coupling is modeled as parasitic capacitances and the magnetic coupling between the air bridges is modeled as parasitic inductances. The series resistance $R_S$ consists of epi-layer resistance, buffer layer...
resistance, finger resistance and ohmic contact resistance as stated in equation (1). Large series resistance can lead to more power dissipation in the diode which increase the conversion loss. Epi-layer resistance can be calculated by equation (2), where $\mu_{\text{epi}}$ is the epi-layer electron mobility, $t_{\text{epi}}$ is the epi-layer thickness, $W(V_J)$ is the depletion layer width, $A$ is anode area, $e$ is the element charge ($1.6 \times 10^{19}$) and $N_{D,\text{epi}}$ is the epi-layer doping concentration. Epi-layer resistance contributes the most to the series resistance as its relatively low doping concentration chosen as $2 \times 10^{17}$ cm$^{-3}$. Buffer layer is highly doped $5 \times 10^{18}$ cm$^{-3}$ to decrease the power dissipation. Zero voltage junction capacitance $C_{j0}$ can be calculated by equation (3) where $D$ is anode diameter, $\varepsilon_s$ is the n-type semiconductor dielectric constant and $V_{bi}$ is schottky junction built-in potential. The cut-off frequency of the schottky diode is 11.3 THz as obtained by equation (4). $I_S$ is the reverse saturation current given by equation (5) where $A$ is anode area, $A^*$ is the effective Richardson constant, $\varphi_B$ is the barrier height, $k_B$ is the Boltzmann constant and $T$ is the junction temperature. These parameters are first theoretically calculated by University of Electronic Science and Technology of China (UESTC) and then fabricated and measured by Hebei Semiconductor Research Institute (CETC-13). Then the parameters are adopted in the ADS to simulate and optimize the whole circuit. Table I shows the main parameters of the schottky diode.

$$R_S = R_{\text{epi}} + R_{\text{ohmic}} + R_{\text{buf}} + R_{\text{finger}}$$

$$R_{\text{epi}}(V_J) = \frac{t_{\text{epi}} - W(V_J)}{eA N_{D,\text{epi}} \mu_{\text{epi}}}$$

$$C_{j0} = \frac{\varepsilon_s A}{W(0)} = A \sqrt{\frac{\varepsilon N_{D,\text{epi}}}{}\frac{2}{V_{bi}}}$$

$$f_c = \frac{1}{2\pi R_S C_{j0}}$$

$$I_S = A A^* T^2 \exp\left(-\frac{e\varphi_B}{k_B T}\right)$$

**Fig. 1.** Top view of the 3D model of diode

**Fig. 2.** Three-dimensional cross-sectional view of the diode
As HFSS doesn’t support the enclosed wave port the anode extends to the epi-layer with coaxial ports depicted in Fig. 3 and then the internal ports are connected to nonlinear model to ground in the ADS. In this way, divide and combine theory are adopted to co-simulate the subharmonic mixer.

### 3 Circuit design

Source and load pull simulations [17] set load/source impedances at harmonic frequencies and vary the source/load reflection coefficients presented to a device to find the optimal value to minimize the conversion loss, schematic diagram of source pull and load pull simulation are shown in Fig. 4.

Optimum embedding impedance for IF is \((120 - j \times 0) \Omega\), LO is \((70 + j \times 5) \Omega\) and RF is \((15 + j \times 15) \Omega\) respectively when the LO pumping power is 5.2 dBm in the HB simulator. In this way, the initial value of the embedding impedance can be obtained to give some design guidance of the matching circuit. Subharmonic mixer configuration is shown in Fig. 5, the whole circuit including the schottky diode is integrated on the 50 um thick quartz suspended in the cavity which miniaturized the circuit size and reduced assembly errors. RF signal passes through rectangular waveguideWR-2.2, LO signal passes through rectangular waveguideWR-4.3 and then the signals are coupled to the diode to generate IF signal. LO low pass filter allows the IF and LO signal to pass through and prevents the RF signal leaking from the LO waveguide because of the waveguide high-pass characteristics. IF low pass filter allows the IF signal to output to the K-connector and prevents the LO signal leaking. Fig. 6 shows the configuration of diode arrangement, (a) is flip-chip
type which require manual assembly, (b) is GaAs monolithic integrated type, the whole circuit is integrated on the 12 \text{um} thick GaAs substrate which required complicated processing technology and more costs, (c) is heterogeneous integrated type, the whole circuit is integrated on the 50 \text{um} thick quartz maintaining similar performance at the same time.

The subharmonic mixer are first divided into several parts in the HFSS including RF waveguide to suspended microstrip line transition, LO low pass filter, LO waveguide to suspended microstrip line transition with IF low pass filter, simulating each part individually, saving as SNP items and then importing the simulation results into ADS to optimize together. Design flow chart is shown in Fig. 7. When the least conversion loss is satisfying, the simulation is completed. The simulated least conversion loss is shown in Fig. 8(a), Fig. 8(b) shows simulated conversion loss when the LO power is 4.5, 5.2 and 5.5 \text{dBm} respectively, least conversion loss can be achieved when the LO drive power is 5.2 \text{dBm}.

![Fig. 5. Circuit configuration of the subharmonic mixer](image)

![Fig. 6. Configuration of diode arrangement](image)

![Fig. 7. Design flow chart](image)
4 Measured results and analysis

The whole circuit is fabricated on the 50 µm thick quartz substrate with schottky diodes integrated on it. Some internal details are shown in Fig. 9 and the 420 GHz subharmonic mixer cavity is shown in Fig. 10. Block diagram of the test platform is shown in Fig. 11 and test platform is shown in Fig. 12. Measured conversion loss is less than 14.7 dB from 400 GHz to 440 GHz and least conversion loss is 10 dB at 419 GHz and 422 GHz when the LO pumping power is 5.2 dBm at 210 GHz as Fig. 13 shows.

There are some tiny differences between simulated and measured results; reasons could be inaccurate diode parameters, cavity and substrate processing precision and manual assembly. Simulated conversion loss is shown in Fig. 14 when the Rs is 7, 10, 15 Ω in (a) and the Cj0 is 1, 2 and 3 fF in (b) respectively. Theoretical analysis indicates that series resistance grows larger, conversion loss is...
deteriorated, the same as zero voltage junction capacitance, they degrades the subharmonic mixer performance. The fluctuation of the measured conversion loss is due to bad RF input standing wave, by using the attenuator [18], it would be greatly improved.

Fig. 11. Block diagram of the test platform

Fig. 12. Test platform

Fig. 13. Measured conversion loss of the subharmonic mixer

(a) (b)

Fig. 14. Simulated conversion loss when the Rs is 7, 10, 15 Ω and the $C_0$ is 1, 2 and 3 fF.
Table II shows state of the art of subharmonic mixer around 400 GHz, heterogeneous integrated 420 GHz subharmonic mixer has shown good performance.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Operating frequency (GHz)</th>
<th>Diode arrangement</th>
<th>Conversion loss (dB)</th>
<th>Measurement configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>356–380</td>
<td>GaAs integrated</td>
<td>8.3</td>
<td>DSB</td>
</tr>
<tr>
<td>19</td>
<td>313–360</td>
<td>discrete</td>
<td>9.78–12.74</td>
<td>SSB</td>
</tr>
<tr>
<td>20</td>
<td>380</td>
<td>discrete</td>
<td>8.5</td>
<td>DSB</td>
</tr>
<tr>
<td>This work</td>
<td>419</td>
<td>Quartz integrated</td>
<td>10</td>
<td>SSB</td>
</tr>
</tbody>
</table>

5 Conclusion

In this paper 420 GHz subharmonic mixer based on heterogeneous integrated schottky diode was successfully designed fabricated and measured. The whole circuit was fabricated on 50 μm quartz instead of the traditional 12 μm GaAs substrate thus the circuit is much easier to manufacture and the cost is much cheaper. Future work will focus on re-extracting the diode parameters to make the simulation results consistent with the test results and eventually the subharmonic mixer will be used in the 420 GHz radiometer system.

Acknowledgments

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