Design of a low noise 190–240 GHz subharmonic mixer based on 3D geometric modeling of Schottky diodes and CAD load-pull techniques

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Abstract: This paper presents the design of a low noise Schottky-diode 190–240 GHz subharmonic mixer (SHM). The embedding impedance condition for the diodes to yield optimum circuit performance is primarily determined. It is achieved using the computer-aided design (CAD) load-pull techniques by taking into account the high-frequency parasitic effects caused by the diode chip geometry. By knowing this condition, the design procedure of the mixer circuitry is expedited. The design effectiveness of the proposed methodology is experimentally validated by the good agreement between the design predictions and the measured results of the mixer performance. Y-factor measurements show that the mixer exhibits the double side band (DSB) noise temperature lower than 1500 K and DSB conversion loss less than 10 dB over the 190–240 GHz frequency range, with the DSB noise temperature and conversion loss at 220 GHz of 800 K and 7 dB respectively.

Keywords: Schottky diodes, 3D model, CAD load-pull, subharmonic mixer, terahertz, 220 GHz

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

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**1 Introduction**

In terahertz (THz) frequency (100 GHz~10 THz) band, subharmonic mixers (SHMs) play a crucial role in heterodyne receivers due to the hardness in developing solid-state amplifiers at the current stage [1, 2]. GaAs Schottky diodes are broadly used as the nonlinear elements in SHMs because of their low noise performance at room temperature [3, 4]. The progress of device fabrication process and the emergence of planar GaAs Schottky diodes make devices’ physical and geometrical structures stable and reliable. The Schottky contact in a planar diode is formed lithographically rather than manually achieved as whisker-contacted diodes.
since the planar diode process brings the merits in terms of device geometrical ruggedness and electrical performance repeatability and thanks to the emergence of commercial three-dimensional (3D) full-wave electromagnetic (EM) simulation software (e.g., ANSYS’s HFSS), it becomes possible to numerically analyze the EM behavior of diode chips. This enables comprehensive insight into the high-frequency parasitic effects caused by the device geometry which exerts unneglectable influences on circuit performance [6, 7], and thus results in effective design of high-performance circuits in THz band. By taking into account of numerical analysis results from the 3D EM modeling of the diode geometry, better agreement between the predictions and measurement results was achieved in [4, 8] compared with the cases in [9, 10] which were based on conventional equivalent circuit modelling of the device geometry.

Furthermore, one of the core issues in the SHM’s design is the synthesis of the embedding network for the Schottky diodes. In order to make design procedure efficient, it is preferable to clarify the optimum embedding impedance condition to make the nonlinear devices yield best noise and conversion loss performance before synthesizing the mixer circuitry. Although these parameters can be assumed to be extracted from load-pull measurements in principle [11], yet it is difficult to be implemented technically in THz band. However, simulation features offered by computer-aided design (CAD) software tools (e.g., Keysight’s ADS) make it possible to set up a load-pull test bench using necessary built-in components and instrument models.

In this paper, we report a low noise Schottky-diode subharmonic mixer in the 190–240 GHz band. The design methodology takes into account the high-frequency parasitic effects from the EM analysis of the diode chip’s 3D geometric model when conducting CAD load-pull simulation to give the optimum embedding impedance condition to achieve best circuit performance. By means of this, the diodes can be linearized and the mixer circuitry is synthesized based on linear simulation, which simplifies and expedites the design procedure. Y-factor measurements show that the mixer’s double side band (DSB) noise temperature is below 1500 K over 190–240 GHz. Good agreement between measurement results and simulation is achieved, which validates the effectiveness of the proposed design method. The broadband and low-noise performance of the mixer can enable high-speed outdoor wireless communication in its frequency band since 220 GHz is an atmospheric window [12].

2 Diode modeling

An anti-parallel Schottky diode pair is the nonlinear element of the SHM which only needs about half of the RF frequency as the local oscillator (LO) pump signal. The diode pair used in this work is AP1 series from the Rutherford Appleton Laboratory [13, 14]. In order to obtain the high-frequency parasitic characteristics introduced by the diode geometry, a 3D diode chip model (shown in Fig. 1) is built in the electromagnetic simulation software HFSS according to the physical and geometrical features based on the diode process [13, 14]. The diode chip is simulated in the actual mounting configuration in a stripline channel and de-
embedded from the stripline access to the chip edge. Each diode port is defined around the anode as a micro-coaxial hollow annular sheet [15]. An integration line is used in the port definition to set the right polarity of the diodes to ensure the right diode connection configuration in the subsequent load-pull and circuit performance simulations.

![3D diode chip model and diode port configuration](image)

**Fig. 1.** 3D diode chip model and diode port configuration

![Schematic diagram of global diode model](image)

**Fig. 2.** Schematic diagram of global diode model

Standard diode models in ADS are used to simulate the nonlinear behavior of the intrinsic Schottky junction. The S-parameters of the diode chip are simulated in HFSS in the RF, LO and IF frequency ranges to present the parasitic characteristics. The simulation results are exported as S-parameter Touchstone files to connect with the diode junction models in ADS. In this way, a global diode model (shown in Fig. 2) is built in ADS which not only presents the nonlinear behavior of the Schottky junctions, but also includes the parasitic effects caused by the diode chip geometry and mounting structure as well. In the ADS simulation bench, ideal built-in filters centered around the RF, LO and IF frequencies are used to achieve the right circuit paths seen by the RF, LO and IF signals [16].

The load-pull simulation is set up within the ADS software suite as schematically displayed in Fig. 3. Harmonic Balance (HB) codes provided in ADS are employed to carry out the noise temperature and conversion loss calculation. By tuning the LO pump power and the impedances at the source ports which provide the input RF and LO test signals in the diode performance simulation environment
(the IF load is set at 100 Ω), the optimum noise temperature and conversion loss of the diode pair can be obtained efficiently with the help of the optimizing function integrated in ADS. As a result, the embedding impedance condition in which the diode pair yields optimum circuit performance can be known. The diode electrical parameters used in ADS are extracted from DC measurements, which are the zero voltage junction capacitance $C_{j0} = 1.4 \text{ fF}$, series resistance $R_s = 12 \Omega$ and ideality factor $n = 1.17$.

From these parameters, the embedding impedance for the RF at 220 GHz and for the LO at 110 GHz are found to be $(78+j30) \Omega$ and $(196+j107) \Omega$ respectively to yield optimum noise performance with the LO power of 2 mW. Furthermore, a diode impedance table including the diode impedance values at the corresponding operational frequencies can also be obtained, which are used to define the diode ports when synthesizing the mixer circuitry. The DSB noise temperature and conversion loss simulated using the global diode model are shown in Fig. 4.

By the use of this modeling method, the possibly optimum diode performance and its embedding impedance condition can primarily be obtained. Consequently, the diode behavior is linearized to generate a diode impedance table, which provides straightforward references to the design of the mixer circuitry to achieve the optimum operation point of the diodes. Since it is easy to change the diode structure in HFSS and the electrical parameters in ADS, this method also provides a way to design diode chips for other THz frequency band applications.
3 Mixer circuitry design

The mixer circuitry configuration is based on an E-plane split-block waveguide architecture shown in Fig. 5. The RF signal comes through a WR-4 rectangular waveguide and is coupled to the diodes via a grounded probe. An RF and dc ground is provided by contacting the end of the stripline to the waveguide wall. The Schottky diode pair chip is mounted across the gap between the gold striplines processed on a 75 µm-thick quartz substrate which is placed in suspended configuration in the waveguide channel. The LO filter prevents the RF signal from leaking through the WR-8 waveguide to the LO input port, but provides the LO power a low loss feeding path to the diodes. By the same token, the IF signal is output through the IF filter without the LO leakage to the IF end. At this end, a K-type connector is used as the IF output port. The reduced height waveguide configuration at both RF and LO probes is optimized for broadband operation.

![Mixer circuitry configuration and the image of the lower part of the assembled mixer block](image)

Fig. 5. Mixer circuitry configuration and the image of the lower part of the assembled mixer block

Each functional passive part of the mixer circuitry including the RF probe transition, LO filter, LO probe transition and IF filter is simulated in HFSS and the results are exported as Touchstone S-parameter files into ADS. With these results and the diode impedance table derived from the global diode model in Section 2, the synthesis of the mixer circuitry for the RF, LO and IF embedding networks can be accomplished only by the use of the linear S-parameter simulator in ADS.

As schematically shown in Fig. 6, these embedding networks realize the impedance matching from the RF and LO ports to the optimum embedding condition and provide the IF signal a low loss output path to achieve possibly best mixer performance. Subsequently, with the synthesized embedding networks and the global diode model, the nonlinear performance of the mixer can also be calculated within ADS (the simulation results are presented in Section 4 in comparison with the measured ones.).
4 Mixer performance characterization

The test setup is shown in Fig. 7. The performance of the assembled mixer was characterized using the Y-factor method at room temperature. Pyramidal blackbody put in front of the feedhorn at room temperature (295 K) and in the liquid nitrogen (LN2) container (80 K) acts as the hot and cold load respectively. The mirror over the LN2 container shown in Fig. 8 provides the feed path for the cold load.

The LO chain is sourced from a frequency sextupler driven by a frequency synthesizer which can supply sufficient pump power for the mixer in the operational frequency range. The tunable attenuator is to adjust the desired output power of the LO chain. An isolator is inserted prior to the mixer’s LO port to prevent potential power reflection. The LO output power was calibrated using an Erickson PM4 power meter.

Fig. 7. Mixer performance test setup

Fig. 8. Picture of the test bench
The experiment was carried out following the Gain Procedure, which is found to be more reliable and described in detail in [17]. The 2–8 GHz IF chain amplifies the mixer’s IF signal up to the power level that the Rohde and Schwarz (R&S) FSU series spectrum analyzer can detect. By presenting alternatively the hot and cold load to the feedhorn input and recording the corresponding IF output power values, the Y-factor and the double side band (DSB) noise temperature of the receiver (including the mixer and the IF chain) can be calculated. To calibrate the IF chain’s Y-factor, a coaxial load via a short length of semi-rigid cable is used to terminate the input of the IF chain, resulting in the hot and cold load respectively when it is at room temperature and immersed in LN₂. Hereby, the mixer’s DSB noise temperature and conversion loss can be extracted according to the equations detailed in [17].

In Fig. 9, the measured DSB noise temperature and conversion loss are presented together with the comparison to the simulation predictions. Good agreement between the measured and predicted results is shown in the figure, which exhibits the measured DSB noise temperature and conversion loss below 1500 K and 10 dB over the frequency range of 190–240 GHz. The LO power used in the measurement is around 3 mW. The lowest DSB noise temperature is measured to be 680 K at 224 GHz.

Table I summarizes the performance of published Schottky SHMs in the similar frequency range. The single side band (SSB) measurement configuration results in the SSB performance indicators and this corresponding relationship is also applicable to the DSB case. Theoretically, the DSB noise temperature and conversion loss are half of the SSB counterparts in term of values [18].

By the use of the proposed design method, the diode nonlinear performance together with the high-frequency parasitic effects caused by its geometry is comprehensively investigated. From this, embedding networks for the diode pair is accordingly designed to ensure good matching which leads to the mixer’s low noise and low conversion loss performance over the broader frequency range.
5 Conclusion

In this paper, a broadband low noise Schottky-diode SHM working in the 190–240 GHz is developed. The design methodology presented in the paper provides a diode-modeling way to determine the embedding impedance condition of the Schottky diodes to yield optimum mixer performance and linearize the diodes at the optimum operation point. With this condition and the diode impedances derived from the linearization, the design procedure of the embedding networks for the diodes can be simplified and expedited. The diode modeling is achieved by adopting the load-pull concept which is realized using the simulation features provided in circuit CAD software ADS together with the use of EM simulator HFSS to look into the high-frequency parasitic effects introduced by the device geometry. The validity of this methodology is tested through experiments. The mixer exhibits a measured DSB noise temperature below 1500 K with conversion loss less than 10 dB in the 190–240 GHz band. Good agreement between the predictions and measurements demonstrates the feasibility and effectiveness of the diode modeling and circuit design methods, which provide a way to design diode chips and SHM circuits in other THz frequency bands. The mixer developed in this paper which operates in the frequency band including an atmospheric window of 220 GHz makes it applicable in wireless communication and imaging systems.

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| Reference | Frequency (GHz) | Noise temperature (K) | Conversion loss (dB) | Measurement configuration |
|-----------|----------------|-----------------------|----------------------|--------------------------|
| [8]       | 210–250        | 950–2000              | 7–10                 | DSB                     |
| [9]       | 215            | 3500                  | 9.2                  | SSB                     |
| [19]      | 200–240        | Not indicated         | 13–22 (typical 16)   | SSB                     |
| this work | 188–244        | 680–1500              | 6.5–10               | DSB                     |