"Terahertz cooled sub-harmonic Schottky mixers for planetary atmospheres"

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Abstract

We report on the design and performance of MMIC sub-harmonic bias able mixer circuits in the 1-2 THz frequency range. Low-parasitic planar GaAs Schottky diodes on membrane technology are used to achieve low noise and wide bandwidth. Sub-harmonic Schottky mixers are ideally suited for space-based planetary exploration since cryogenic cooling is not required and the local oscillator is at half the RF signal. On-chip biasing capability allows one to design optimum receiver performance with lower local oscillator power. A 830-900 GHz sub-harmonic mixer chip has been fabricated and packaged in a conventional waveguide block. With sufficient LO power the receiver demonstrates a double side-band (DSB) receiver noise temperature of 5000-6000 K over a substantial range of frequencies. The receiver performance is also characterized around the 120 K range (often achievable with passive coolers in space). Preliminary measurements indicate that the receiver sensitivity is enhanced by a factor of 1.7 as the mixer and LO chain are cooled to 120 K. Further improvement is expected by cooling the 1st IF Low Noise Amplifier as well.

Keywords: terahertz MMICs, planar Schottky diode, sub-harmonic mixer modeling, cryogenic testing.

INTRODUCTION

The THz frequency range is rich in emission and absorption lines of various molecular species whose detection and mapping are important to understand the atmospheric circulation of outer planets (Saturn, Jupiter) and their moons (i.e. Titan, Ganymede). For instance, methane (CH4), carbon monoxide (CO), HCN and CS have strong spectral signatures lying in the range between 1 and 2.2 THz. Schottky diode based heterodyne instruments have demonstrated high sensitivity and high spectral resolution up to 2.5 THz while operating at room temperature. This technology is envisaged for future atmospheric remote sensing instruments onboard several proposed missions such as LAPLACE, TANDEM (ESA/NASA candidate missions to the Outer Planets) [1], as well as future Mars missions. Furthermore, high frequency sub-millimeter channels at 664 and 874 GHz are envisaged for future Earth atmospheric remote sensing missions (e.g. CIWSIR/GOMAS Explorer mission proposals to ESA) specifically dedicated to the monitoring of ice clouds in the upper troposphere-lower stratosphere [2]. Recent breakthroughs, such as in-phase power combining, has enabled multiplied sources in the ~1 THz range with a milliwatt of output power [3]. Better thermal management of high power multiplier devices is also an important consideration for robust designs [4] and is an important tool for increasing long term reliability. These improvements open the door for complete solid-state, broadband Schottky based heterodyne receivers to operate up to at least 2 THz at room temperature using sub-harmonic Schottky mixers. Moreover, Schottky based receivers' sensitivity can be enhanced by cooling them to temperatures that are achievable in space via passive cooling techniques.

This paper will detail the design and development of MMIC Schottky diode sub-harmonic mixers from 0.9 THz up to 2 THz. First, the design of a 810 to 910 GHz sub-harmonic mixer previously described [5] has been "scaled" to cover various bands in the 1-2 THz range. The general architecture and predicted performances are presented. In order to take into account some electrical effects which might be of importance at THz frequencies, such as the displacement capacitance and carrier inertia, a custom electrical model of the Schottky barrier has been developed and incorporated into commercially available software (such as ADS) by means of a Symbolically Defined Device (SDD). Predicted performances give DSB mixer conversion losses between 10 and 13 dB and DSB noise temperature between 2500 K and 5000 K at room temperature from 1 to 2 THz. Secondly, a robust cryogenic test set-up for Schottky mixers has been developed to test Schottky mixers at room and cryogenic temperatures, in an environment compatible with passive cooling (250 to 80 K) in space (vacuum). Finally, preliminary test on the 810-910 GHz sub-harmonic mixer have been performed and DSB receiver noise temperature for room and cryogenic temperatures are presented. When operated in the 100 K temperature range, the receiver noise temperature is expected to drop by a factor of 1.7 compared to room temperature operation.

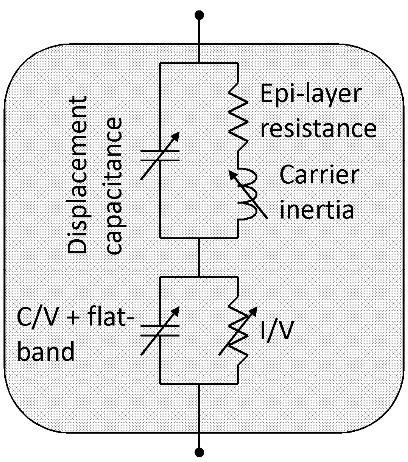
CUSTOM SCHOTTKY DIODE MODEL FOR TERAHERTZ FREQUENCIES USING SYMBOLICALLY DEFINED DEVICES

At terahertz frequencies, several studies have shown that high frequency effects associated with plasma resonance in the doped GaAs epi-layer material can influence the performance of the mixer and therefore have to be included in the electrical model of the Schottky diode [6][7]. The standard ADS software suite (from Agilent [8]) model of the Schottky barrier does not include effects such as displacement capacitance, carrier inertia, and capacitance-voltage behavior above flat-band. Furthermore, the standard ADS Schottky noise model does not consider the heating of the electrons when passing through the Schottky barrier. We present here two complementary electrical models of the Schottky diode, one used to compute the conversion losses at terahertz frequencies, the other used to more accurately predict noise performance at ambient temperature. A schematic view of the custom SDD Schottky model and standard ADS Schottky model with improved noise model are shown in Fig. 1a&b.

A custom ADS electrical model of the Schottky barrier that uses the Symbolically Defined Devices (SDD) toolbox has been developed specifically for the prediction of conversion losses and optimal embedding impedances necessary to accurately design MMIC Schottky mixers at terahertz frequencies. This custom SDD electrical model is presented in Fig. 1a. It also includes modified C/V equations above flat-band [9] that can more accurately reflect device operation. This part of the SDD model has been validated on a broadband 170-200 GHz MMIC frequency doubler [10]. The SDD model also includes a non-linear capacitance contribution of the displacement capacitance and a non-linear inductance from the contribution of the carrier inertia, as given by [6]. It is believed that these effects play an increasing important role when the frequency of operation of Schottky devices gets closer to the plasma resonance of doped GaAs. Simulation results on terahertz sub-harmonic mixers presented in the next section seem to confirm this assumption. Finally, I/V equation defined in the SDD is similar to the one used in the standard ADS Schottky model [8].

A custom noise model of the Schottky barrier that approximates the effect of hot electron noise in addition to the standard shot and thermal noise embedded in the ADS Schottky diode model has already been reported [11] and is used here. A schematic drawing of this Schottky noise model is presented in Fig. 1b. In order to compute the total mixer noise temperature using ADS, a first simulation of the mixer circuit including the standard ADS Schottky model is performed to determine the harmonic LO currents passing through the diode. In a second step, an external noise source proportional to the sum of the square of the harmonic LO currents is added in series to the Schottky diode model, and the mixer noise temperature is computed. This model has been validated on a 330 GHz sub-harmonic mixer using an anti-parallel pair of planar Schottky diodes [12].

Unfortunately, until now, it is not possible to use SDD to predict noise performance with ADS, and therefore have one single custom Schottky model for conversion losses and noise temperature at the same time. Therefore, two separate models are still needed. Moreover, only room temperature noise predictions are believed to be relevant as harmonic currents change at cryogenic temperature and therefore affect the shot and hot electron noise generation. Further development of the model will therefore include a temperature dependent I/V curve for cryogenic operation.



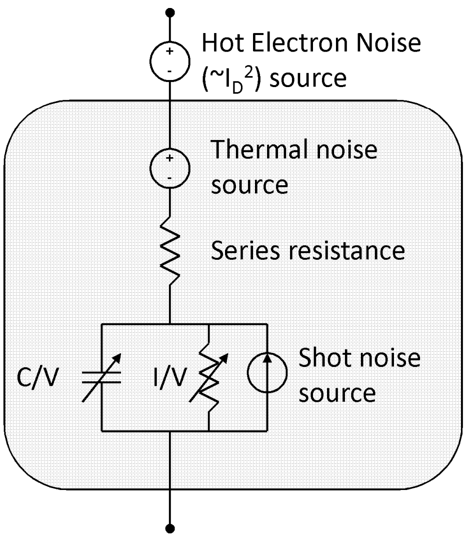


Fig. 1a&b. Left hand side: custom ADS Schottky model that uses Symbolically Defined Device (SDD) for operation above 1 THz . Right hand side: standard ADS Schottky electrical and noise model with the added Hot Electron Noise source .

DESIGN OF TERAHERTZ MMIC BIASABLE SUB-HARMONIC MIXERS IN THE 1-2 THZ RANGE

The design of 1-2 THz MMIC sub-harmonic biasable mixers is based on the successful 874 GHz mixer topology described previously [5]. Four different devices have been designed to respectively cover the following bands: 0.93-1.1 THz, 1.1-1.3 THz, 1.35-1.5 THz and 1.75-2 THz. A generic mixer device is shown in Fig. 2. As previously, both Schottky diodes on the circuit are in a balanced configuration. A MIM on-chip capacitor allows to bias the diodes and therefore reduce the amount of required LO power which is desirable especially at the high end of the LO frequency range (1 THz). The devices use a thin GaAs membrane (a few microns thick) and are suspended inside the cross-channel between the LO and RF waveguides using four grounded beamleads, and connected to an IF output circuit using a fifth beamlead. The circuit has been optimized using a combination of 3D EM simulations from Ansoft-HFSS [13] and linear/harmonic balance simulations from Agilent-ADS [8]. The methodology has been already presented elsewhere and will not be described any further

The predicted performance for room temperature operation are shown in Fig. 3 and Fig. 4. In addition to the four circuits presented above, the predicted performance of the 810-910 GHz sub-harmonic mixer tested previously is also represented for comparison (blue curve on the left). The conversion losses are calculated using the Harmonic Balance code of ADS. A series resistance in the range 20 to 25 Ohms depending on the circuit is assumed, with an ideality factor of 1.3, and built-in potential of 0.8 V. The IF frequency and impedance are set to 5 GHz and 100 Ohms respectively.

For the DSB conversion losses, Fig. 3a&c shows the simulation results for the standard ADS (as shown in Fig. 1b) and Fig. 3b&d for the custom SDD Schottky models (as shown in Fig. 1a), for both unbiased (see Fig. 3a&b) and biased (see Fig. 3c&d) configurations. For the un-biased configuration, an LO input power of 4 mW is assumed for the circuits up to 1.5 THz, and 6 mW is assumed for the 1.75-2 THz one. For the biased configuration, an LO power of 1.5 mW at half the RF frequency, and a bias voltage of 1V for both diodes in series is assumed.

To predict the DSB mixer noise temperature at room temperature, only the standard ADS Schottky diode noise model enhanced with Hot Electron Noise source is used (see Fig. 1a). Fig.7a shows the DSB mixer noise temperature for un-biased configuration, and Fig. 4b for the biased configuration, with similar LO power and DC bias values as before.

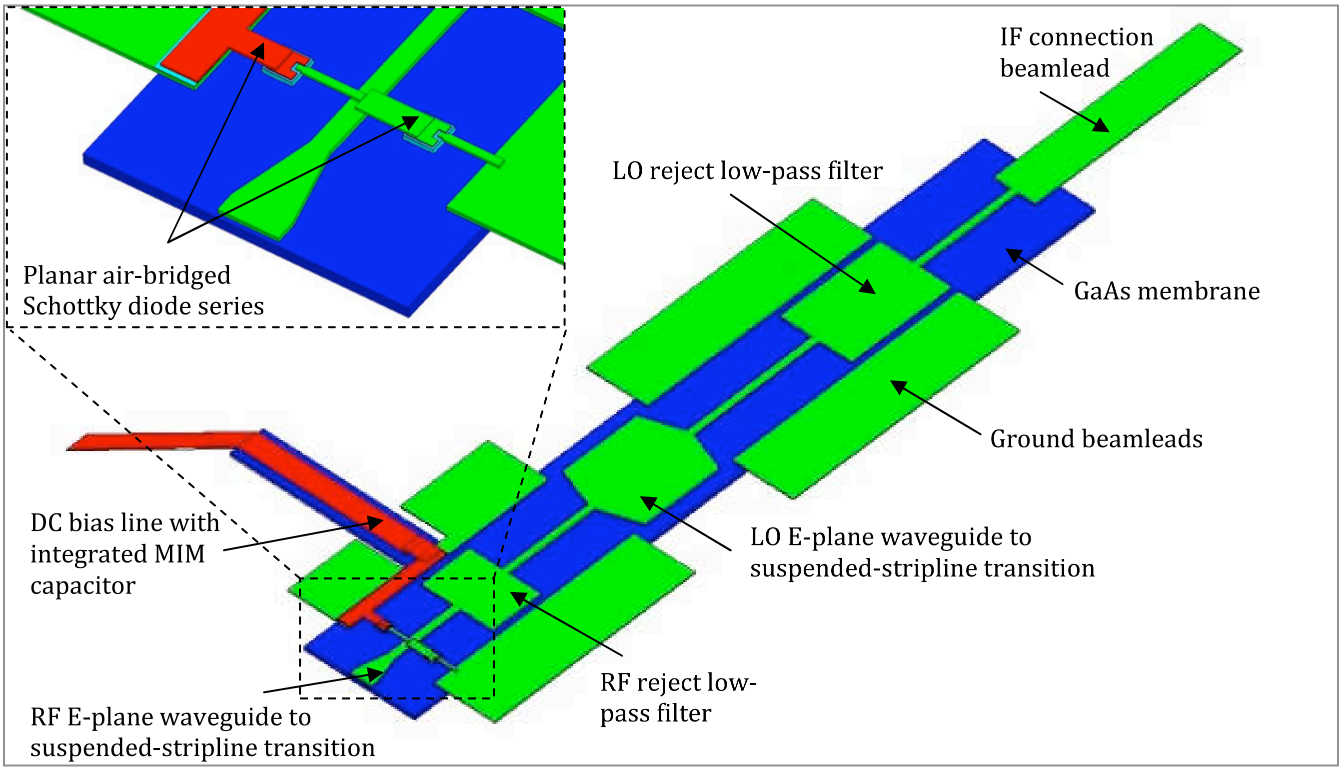


Fig. 2. Isometric view of a generic MMIC membrane biasable sub-harmonic mixer chip. The chip can be "scaled" for various frequency ranges: 0.9-1.1 THz, 1.1-1.3 THz, 1.35-1.5 THz and 1.75-2 THz.

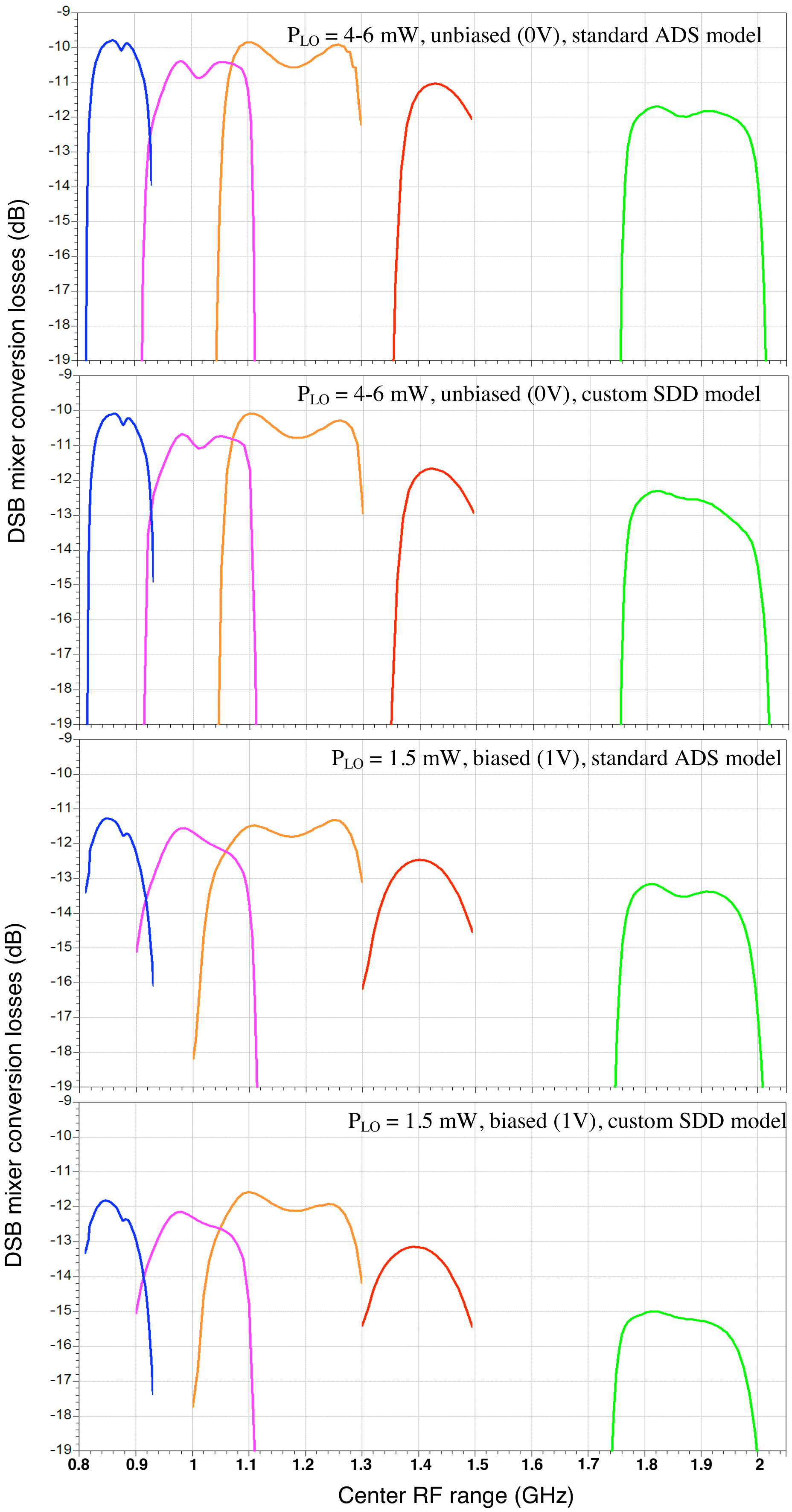


Fig. 3a-d. Predicted DSB mixer conversion losses for room temperature operation in the range 0.8-2 THz. Fig. 3a&c use the standard ADS model, whereas Fig. 3b&d use the custom ADS model using SDD. Fig. 3a&b are for unbiased devices and 4-6 mW of LO power, Fig. 3c&d are for biased devices at 1V for both diodes and 1.5 mW of LO power.

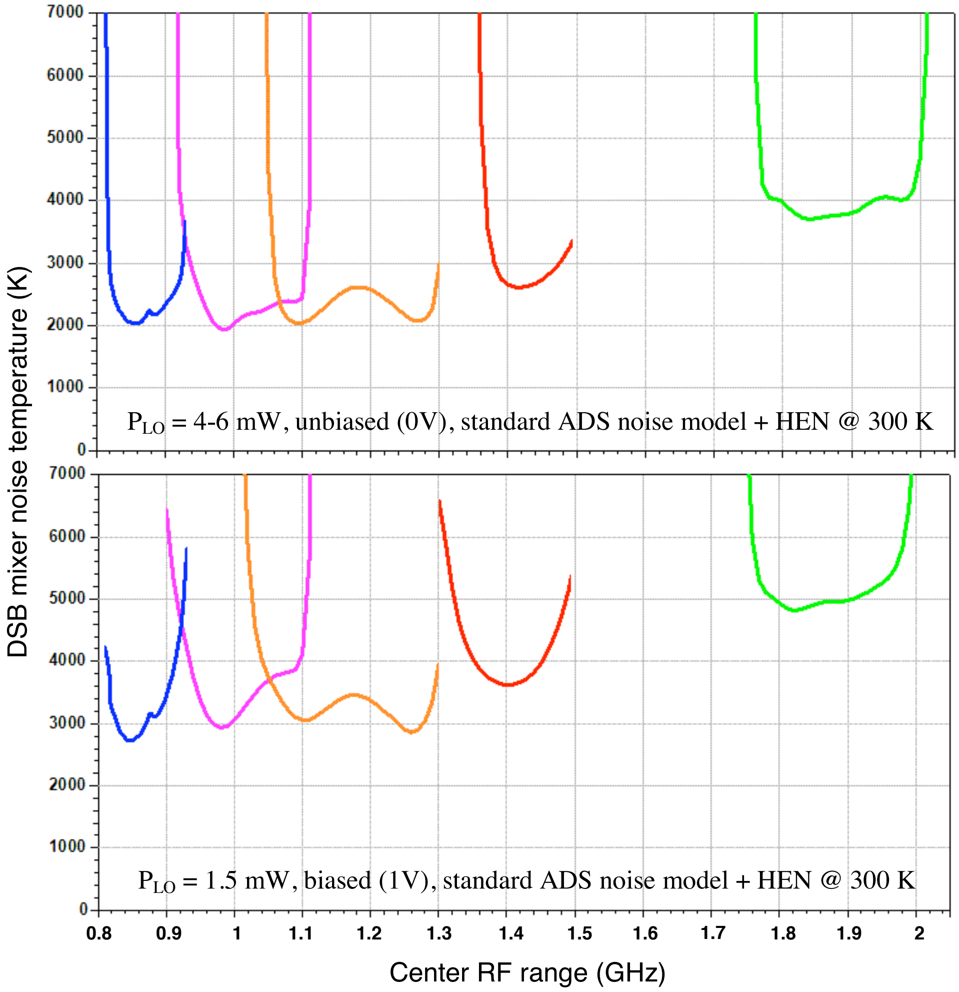


Fig. 4a&b. Predicted DSB mixer noise temperature for room temperature operation in the 0.8-2 THz range. It uses the standard ADS Schottky noise model enhanced with Hot Electron Noise source. In the unbiased case (Fig. 4a), LO power is 4-6 mW. In the biased case (Fig. 4b), LO power is 1.5 mW and applied voltage is 1V for both devices.

As shown in Fig. 3a-d, the predicted DSB mixer conversion losses extend from 10 to 12 dB using the standard ADS model, and 10 to 13 dB using the custom SDD model when the mixer is pumped with enough LO power and without bias. When pumped with only 1.5 mW and biased, the DSB mixer conversion losses degrade by up to 1 dB for the standard ADS model and by up to 2 dB with the custom SDD model. It is also noticed that at higher frequencies, the custom SDD model predicts higher conversion losses than the standard ADS model, which is expected from the plasma frequency effects described previously.

From the simulation results obtained in Fig. 4a&b, it can be seen that the predicted DSB mixer noise temperature ranges from 2000 to 4000 K when the device is pumped with sufficient LO power and without biasing, and from 3000 to 5000 K when pumped with 1.5 mW of LO power and biased at 1V. These values are for room temperature operation.

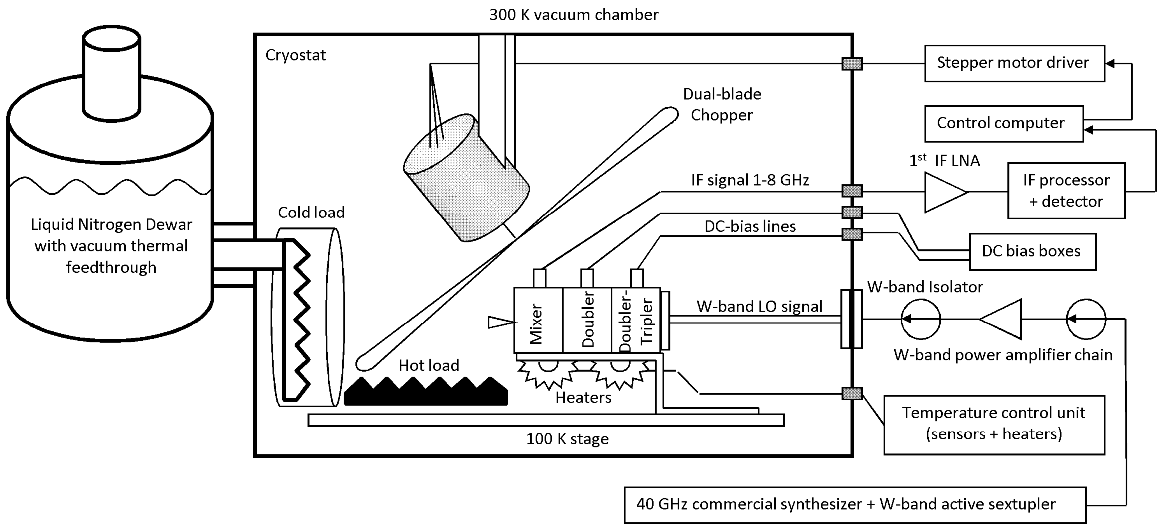


Fig. 5. Schematic view of the cryogenic vacuum mixer test bench. The hot and cold calibration targets are inside the vacuum test chamber. The chopper blade is suspended from the 300 K lid inside the vacuum chamber.

VACUUM CRYOGENIC TEST BENCH FOR TERAHERTZ SCHOTTKY MIXERS

In order to perform measurements on sub-millimeter wave sub-harmonic mixers at room and cryogenic temperatures, a cryogenic test bench has been developed and is presented here. The test bench includes a vacuum cryogenic chamber connected to a vacuum pump and a cryo-cooler head, liquid nitrogen external Dewar, various DC/IF and RF vacuum feed-through connectors, couple of vacuum windows, and internal hot/cold loads and a chopper blade. A schematic view of the test set-up is shown in Fig.5.

To generate the LO signal, a commercial synthesizer followed by an active sextupler and a W-band amplifier chain is used to produce more than 150 mW in W-band. This powerful signal is then fed into the cryogenic test chamber via a W-band flange vacuum feed-through to the following multipliers. The receiver front-end, composed of multipliers and sub-harmonic mixer, is thermally connected to the cold 100 K stage of the test chamber and temperature controlled by a couple of 25 W heaters mounted on the bottom of the bracket. The vacuum stepper motor and the gold plated 2-blade chopper is suspended from the lid of the vacuum chamber to present alternatively a hot and cold load to the mixers' feed-horn antenna. The hot load sitting on the bottom of the test chamber is isolated thermally from the cold stage. The cold load inside the test chamber is connected thermally to a liquid nitrogen Dewar positioned outside the test chamber. This Dewar has a thermal vacuum feed-through specially designed to avoid breaking the vacuum inside the chamber while cooling the cold load. DC and IF signal are connected to bias boxes and an IF pre-amplifier outside the test chamber via DC/IF vacuum feedthroughs. Finally, a fully automated IF processor, including filters, power detectors, and a computer that records the signal levels and drives the stepper motor is used to measure the Y-factor of the receiver chain.

CRYOGENIC TEST OF AN 874 GHZ MMIC MEMBRANE SUB-HARMONIC MIXER

The design and development of an 874 GHz sub-harmonic mixer at room temperature and pressure have already been reported [5]. It uses MMIC Schottky diode devices fabricated at JPL using their MoMeD process [14]. A view of the circuit is shown in Fig. 6 (right).The LO signal required to pump the mixer is produced by cascading the right combination of multipliers preceded by W-band power amplifiers. The 400-432 GHz frequency range is covered with a x2x2 combination that produces around 3.5 to 5 mW. Beyond 432 GHz, a x3x2 chain is employed. This chain puts out 2.4-4.5 mW of output power in the 432-438 GHz range. Above 438 GHz, the output power of this chain drops below 2.5 mW causing the mixer to be severely under-pumped. Fig. 6 (left) shows the mixer block along with the x2x2 LO chain.

The DSB receiver noise temperature of the 874 GHz MMIC membrane sub-harmonic mixer for 295 K, and 120 K is presented in Fig.7. It includes the contributions from the mixer located inside the vacuum cryogenic test chamber, first IF amplifier is located outside the test chamber, and the IF processor used in the automated detection and control system. The first IF amplifier has approximately 1 dB of Noise Figure between 1 and 2 GHz, and 30 dB of gain.

Fig. 6: view of the compact 874 GHz receiver front-end including 200 and 400 GHz doublers, and an 874 GHz sub-harmonic mixer (left hand side). The membrane based biasless chip used for the mixer is shown on the right.

As shown in Fig. 7, at room temperature, the receiver noise temperature ranges from 5200 K to 6000 K from 840 GHz up to 872 GHz. These values are consistent with independent measurements of the DSB mixer noise temperature ranging from 3000 K to 4000 K, with 11 to 13 dB of estimated DSB conversion losses Above 872 GHz, the tripler + doubler LO chain does not give enough power at room temperature to reach optimal performance of the mixer, and receiver noise temperature degrades significantly.

When the mixer is physically cooled to the 80 - 120 K range, the DSB receiver noise temperature drops down to the 3000 K to 4000 K range. If the conversion losses are assumed to remain similar while cooling at about 11-13 dB, the resulting DSB mixer noise temperature drops from 4000 K to about 2500 K, giving an improvement in the DSB mixer noise temperature of at least 2 dB as previously reported [15]. Further cooling at 80 K of physical temperature has led to best DSB receiver noise temperature measured was 3000 K at 888 GHz. Additional measurements are currently in progress to further characterize this mixer/receiver, and to test the receiver with a cold IF low noise amplifier.

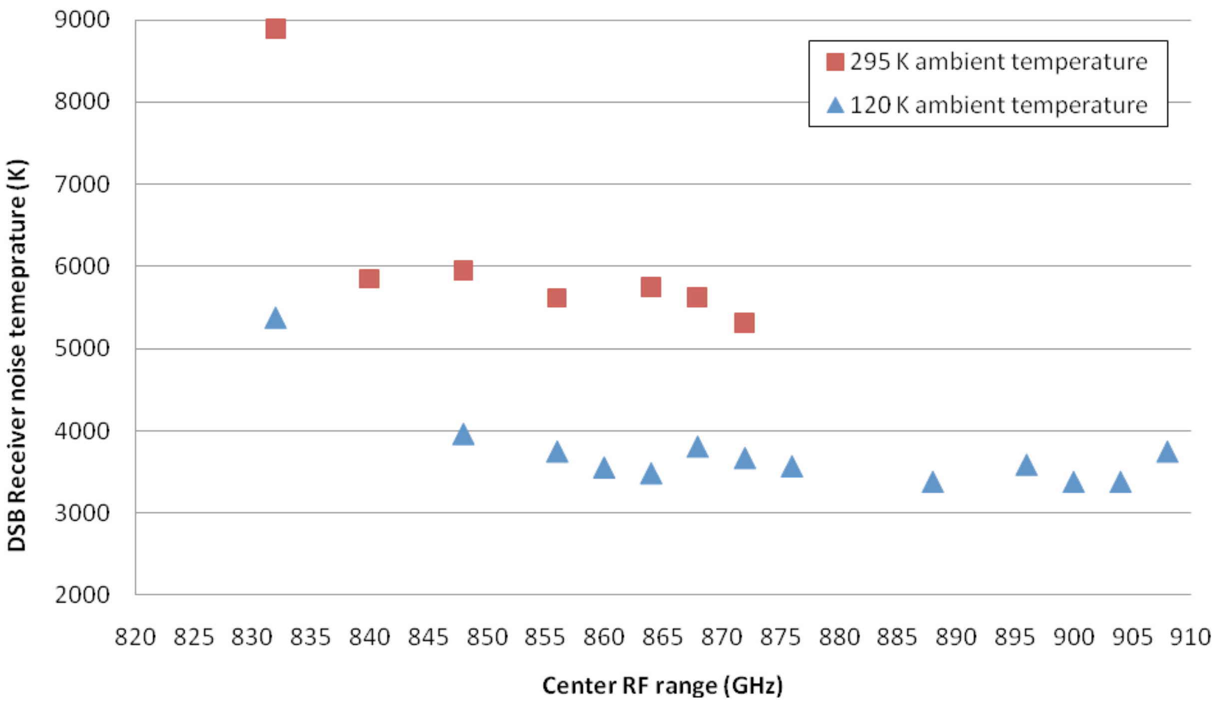


Fig.7. Performance of the 874 GHz receiver chain for 295 K and 120 K temperatures operation. The sub-harmonic mixer is located inside the cryogenic test chamber, whereas the first IF amplifier is located outside the chamber.

CONCLUSION

The design and predicted performance of GaAs Schottky diode based sub-harmonic mixers between 1 and 2 THz has been presented. In order to accurately model the behaviour of the Schottky barrier at terahertz frequencies, a custom electrical model that uses physics-based device phenomena has been developed and integrated into the mixer simulation software. These devices are expected to give DSB mixer noise temperatures below 5000 K and 13 dB of conversion losses. A cryogenic test set-up has been developed to test Schottky diode mixer performance at lower temperatures consistent with passively cooled approaches in space. Preliminary results on a 830-910 GHz sub-harmonic mixer indicate that performance enhancement of approximately 1.7 in the receiver sensitivity is obtainable when the mixer and LO chain are cooled from 300K to 120K. This opens the possibility of highly sensitive all-solid-state broad bandwidth receivers in the terahertz domain for future passively cooled heterodyne instruments dedicated to the remote sensing of planetary atmospheres.

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