Sub-millimeter wave MMIC Schottky sub-harmonic mixer testing at passive cooling temperatures

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Abstract— **We report on the development of a cryogenic test bench for millimetre, sub-millimeter and terahertz MMIC Schottky mixers. The test set-up is used to measure an 874 GHz MMIC membrane sub-harmonic mixers at 300 and 120 K of ambient temperature, in vacuum environment. When cooled to temperatures compatible with passive cooling in space (120 K range), a DSB receiver noise temperature of approx. 3500 K with best value at 3000 K is obtained in the frequency range 850-910 GHz. Based on the latter topology, sub-harmonic mixer design has been extended up to 2 THz. It uses a novel custom Schottky electrical Schottky model compatible with ADS software suite to take into account effects related to the plasma resonance in doped GaAs at terahertz frequencies. Predicted performance is presented for room temperature operation.**

Index Terms— **cryogenic test setup, terahertz frequencies, MMIC membrane Schottky sub-harmonic mixer, modeling.**

I. INTRODUCTION

The sub-millimeter wave and terahertz 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 planets. For instance, methane (CH4), carbon monoxide (CO), HCN and CS have strong spectral signatures lying in the range between 1 and 2.2 THz [1]. Schottky diode based heterodyne instruments have demonstrated high sensitivity and high spectral resolution up to 2.5 THz while operating at room temperature. Sub-millimeter wave heterodyne instruments that use such devices are envisaged for future atmospheric remote sensing instruments onboard several proposed missions such as LAPLACE, TANDEM (ESA/NASA candidate missions to outer planets) for Jupiter and Saturn [2], as well as future Mars/Venus missions. Moreover, future Earth observation missions dedicated to the monitoring of ice clouds in the troposphere/stratosphere could use frequency channels operating as high as 874 GHz, giving valuable information on the ice cloud particles size and their spatial distribution [3].

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In that context, we report on the current status of development of MMIC Schottky diode sub-harmonic mixers from 0.5 THz up to 2 THz. First, a sub-millimeter wave sub-harmonic mixers centered at 874 GHz has been tested at room (295 K) and cryogenic (120 K) temperatures. For this purpose, a robust cryogenic test set-up for Schottky mixers has been developed and is presented hereafter. The amount of improvement that can be obtained by cooling it to temperatures compatible with passive cooling in space (approx. 120 K) has been quantified and is also presented.

Following the development of this prototype, the design of MMIC Schottky sub-harmonic mixers has been extended to cover various bands within the 1-2 THz range. 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 the ADS software by the mean of a Symbolically Defined Device (SDD). Predicted performances give best DSB mixer conversion losses between 10 and 15 dB and DSB noise temperature between 2500 K and 5000 K at room temperature from 1 to 2 THz. When operated in the 120 K temperature range, the receiver noise temperature is expected to drop by a factor of 2.

II. CRYOGENIC TEST SETUP FOR SCHOTTKY MIXER TESTING

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 feedthrough connectors, couple of vacuum windows, and internal hot/cold loads and chopper blade. An external and internal view of the cryogenic test set-up is presented in Fig.1 and Fig. 2 respectively.

To generate the LO signal, a commercial synthesizer followed by an active sextupler and a series of power-combined 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 the 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. Above the front-end chain, a vacuum stepper motor and gold plated 2-blades 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 drive the stepper motor is used to measure the Y-factor of the receiver chain.

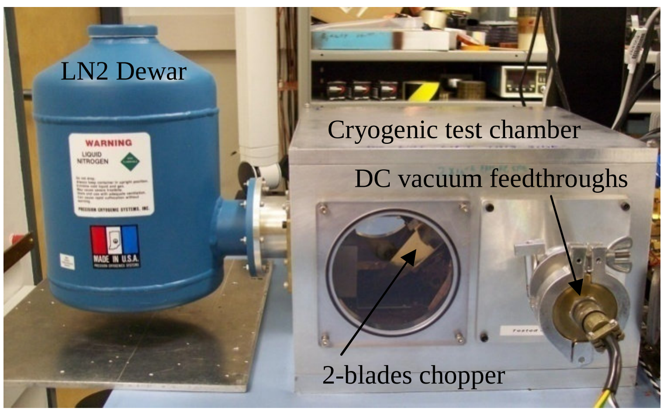

Fig.1. General view of the cryogenic test set-up used to characterize mixers at cryogenic temperatures (compatible with passive cooling in space).

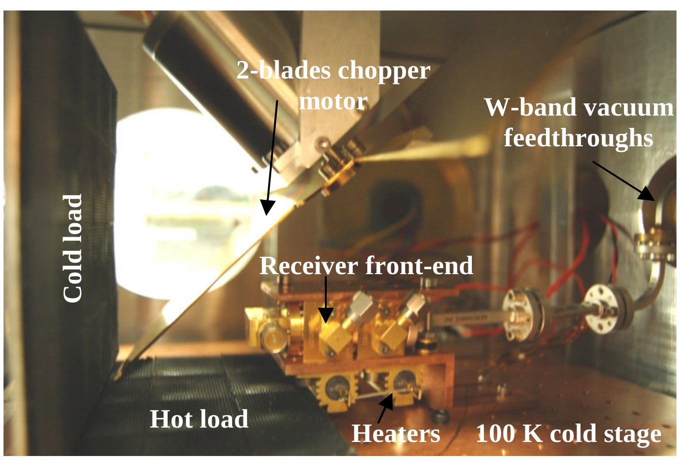

Fig. 2. Internal view of the cryogenic vacuum mixer test bench. The hot and cold calibration targets are inside the vacuum test chamber. The chopper blade is suspended from the 295 K lid inside the vacuum chamber. The cold target is thermally connected to an external liquid nitrogen Dewar shown in Fig. 1. The receiver front-end (multipliers and mixer) are attached to a copper bracket thermally connected to the 100 K stage of the chamber.

III. Cryogenic Testing of Sub-Millimeter MMIC Membrane Sub-Harmonic Mixer

An 874 GHz front-end chain has been tested. The Local Oscillator for the 874 GHz mixer is provided by either a 200 GHz doubler + 400 GHz doubler, or a 220 GHz tripler + 440 GHz doubler. A view of the 874 GHz front-end chain that includes both doublers and sub-harmonic mixer is shown in Fig. 3. Further details about the doublers design and performances can be found in [4], and for the sub-harmonic mixer in [5].

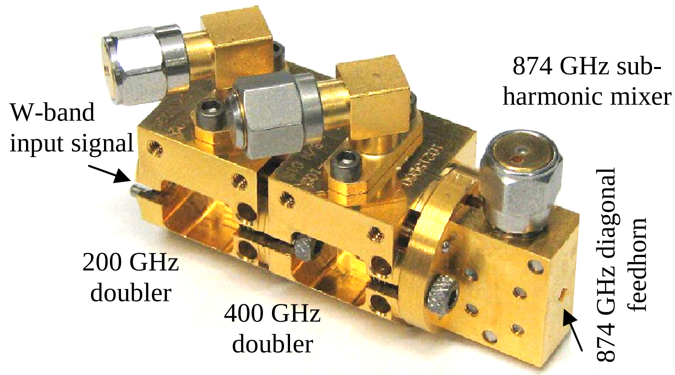

Fig.3. View of the 874 GHz receiver front-end, including a 200 GHz and 400 GHz doubler, and 820-910 GHz sub-harmonic mixer (on the right).

As indicated, several LO chains are required to cover the bandwidth of the 820-910 GHz sub-harmonic mixer, as the latter is unbiased and needs between 3 and 5 mW of input power in the 440 GHz range. As shown in Fig. 4, two chains are used to cover the 405-442 GHz frequency range when operating at room temperature. The output power was recorded with an Erickson calorimeter PM3 [6]. When cooled to 120 K, the tripler + doubler chain can output enough power to pump the mixer up to 450 GHz as shown in the next section.

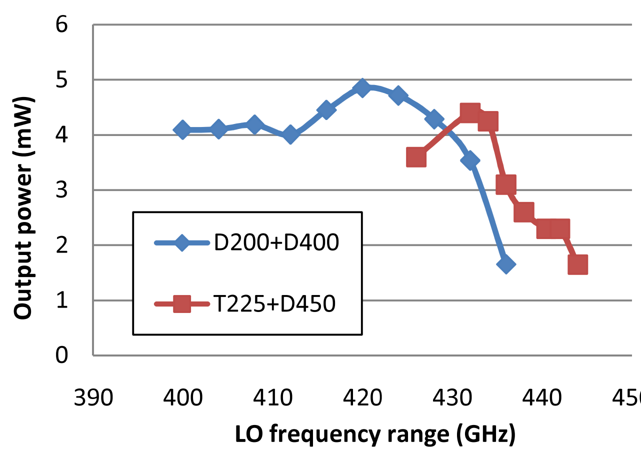

Fig.4. Output power of both LO chains used to drive the 874 GHz sub-harmonic mixer VS output frequency at room temperature. The 1st chain includes 200 GHz and 400 GHz doublers (blue diamonds), the 2nd 220 GHz tripler and 440 GHz doubler (red square).

A. Test results at 874 GHz

The DSB receiver noise temperature of the 874 GHz MMIC membrane sub-harmonic mixer for 295 K and 120 K of ambient temperatures is presented in Fig.5. As previously mentioned, it includes the contribution from the mixer, 1st LNA and IF processor chain. As shown in Fig. 5, at room temperature, the receiver noise temperature ranges from 4680 K to 6280 K from 840 GHz up to 885 GHz at room temperature (295 K). These values are consistent with independent measurements of the DSB mixer noise temperature ranging from 3000 K to 4000 K, with approx. 11.5 to 13 dB of estimated DSB conversion losses [5]. Above 885 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.

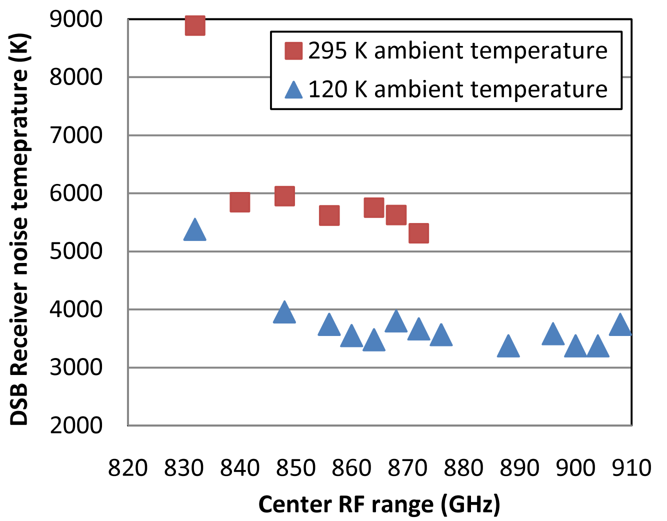

Fig.5. 295 K (red squares) and 120 K (blue triangles) ambient temperature performance of the 874 GHz receiver chain. The sub-harmonic mixer is located inside the cryogenic test chamber, whereas the 1st LNA is located outside and therefore always at room temperature.

When the mixer is physically cooled to 120 K, the DSB receiver noise temperature drops down in the 3000 K to 4000 K range. If the conversion losses are assumed to remain similar at about 11.5-13 dB while cooling, the resulting DSB mixer noise temperature drops from 4000 K to about 2500 K, giving an improvement in the DSB mixer noise temperature close to 2 dB as previously reported [7]. At 80 K of physical temperature, the best DSB receiver noise temperature measured was 3000 K at 888 GHz central RF range.

Further measurements are on-going to characterize accurately the DSB mixer noise temperature and DSB conversion losses in this frequency range *VS* operating temperature.

IV. 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 has to be included in the electrical model of the Schottky diode [8][9]. The standard ADS software suite (from Agilent [10]) 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 predict more accurately noise performances at room temperature. A schematic view of the custom SDD Schottky model and standard ADS Schottky model with improved noise model are shown in Fig. 6a&b.

First, 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. 6a. It also includes modified C/V equations above flat-band [11]. This part of the SDD model has been validated on a broadband 170-205 GHz MMIC frequency doubler [12]. The SDD model also includes a non-linear capacitance from the contribution of the displacement capacitance and a non-linear inductance from the contribution of the carrier inertia [8]. It is believed that these effects play an increasing important role when the frequency of operation of Schottky devices is getting 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, the I/V equation defined in the SDD is similar to the one used in the standard ADS Schottky model.

Second, 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 [13] and is used here. A schematic drawing of this Schottky noise model is presented in Fig. 6b. 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 diode [14]. This model is used to predict mixer noise performances at terahertz frequencies, as shown in the next paragraph.

Unfortunately, until now, it is not possible to use an 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 so far. 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.

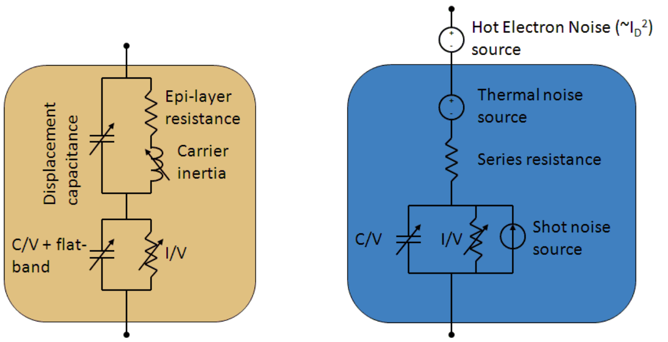

Fig. 6a&b. Left: custom ADS Schottky model that uses Symbolically Defined Device (SDD) for operation above 1 THz. Right: standard ADS Schottky electrical and noise model with enhanced Hot Electron Noise model (top).

V. 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 based on the successful 874 GHz mixer topology [5] is presented here. Four different devices have been designed to cover respectively 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 version of the mixers' architecture is shown in Fig. 7. As previously, both Schottky diodes on the circuit are in a balanced configuration. A MIM chip capacitor integrated to the circuit allows to forward bias the diodes and therefore reduce the amount of LO power required which is desirable especially at the high end of the LO frequency range (1 THz). The devices that use a thin GaAs membrane (typ. few microns thick) 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 predicted performances for ambient temperature operation are shown in Fig. 8&9. In addition to the four circuits mentioned above, the predicted performance of the 810-910 GHz sub-harmonic mixer tested previously is also given for comparison. The conversion losses are calculated using the Harmonic Balance code of ADS.

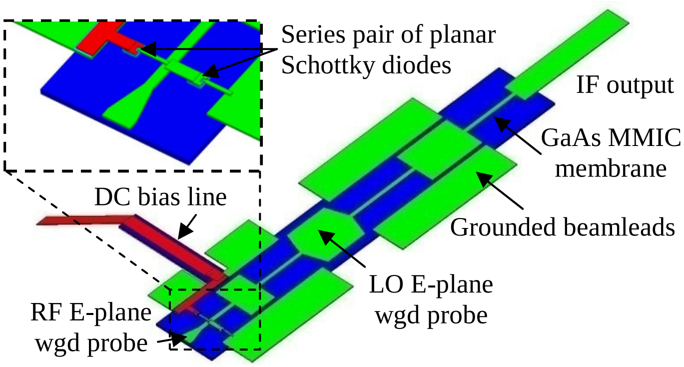

Fig.7. Isometric view of a generic MMIC membrane biasable sub-harmonic mixer chip. The chip is further "scaled" for various frequency ranges: 0.9-1.1 THz, 1.1-1.3 THz, 1.35-1.5 THz and 1.75-2 THz.

A series resistance in the range 20 to 25 Ω 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 Ω respectively.

For the DSB conversion losses, Fig. 8a&b shows the simulation results for the custom SDD Schottky models (as presented in Fig. 6a), for both unbiased (see Fig. 8a) and biased (see Fig. 8b) 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. 6b). Fig. 9a shows the DSB mixer noise temperature for un-biased configuration, and Fig. 9b for the biased configuration, with similar LO power and DC bias values as before.

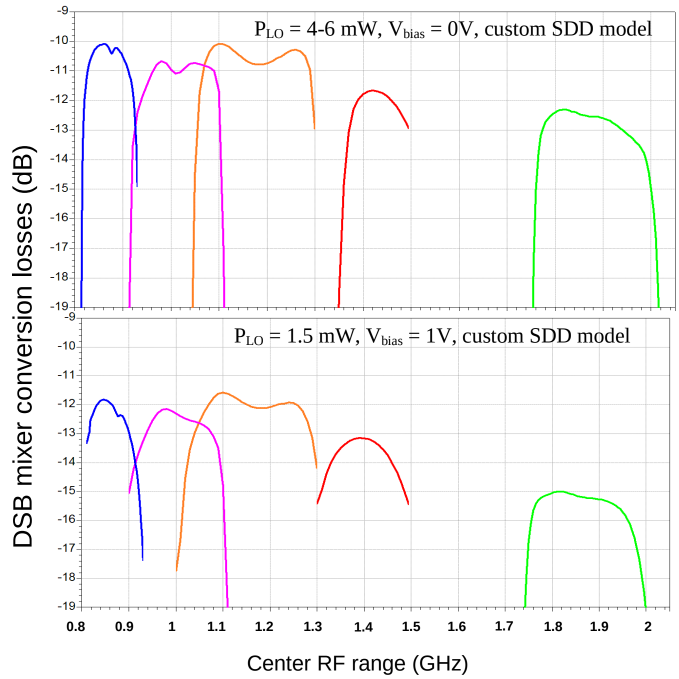

Fig. 8a&b. Predicted DSB mixer conversion losses for room temperature operation in the range 0.8-2 THz, using the custom SDD model. Fig. 8a are for unbiased devices and 4-6 mW of LO power, Fig. 8b are for biased devices at 1V for both diodes and 1.5 mW of LO power.

As shown in Fig. 8a&b, the predicted DSB mixer conversion losses extend from 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 2 dB. From the simulation results obtained in Fig. 9a&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.

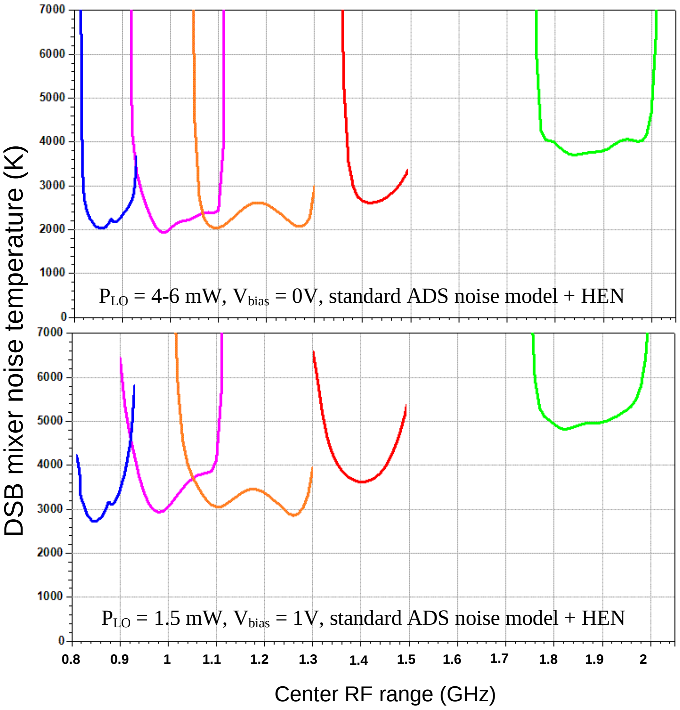

Fig. 9a&b. Predicted DSB mixer noise temperature for room temperature operation in the 0.8-2 THz range. It uses the standard ADS Schottky noise model enhanced with Hot Electron Noise source. In the unbiased case (Fig. 7b), LO power is 4-6 mW. In the biased case (Fig. 7b), LO power is 1.5 mW and applied voltage is 1V for both devices.

Finally, an example of the proposed architecture for an all-solid-state room temperature or passively cooled terahertz heterodyne receiver front-end is shown in Fig. 10. The LO chain relies on power-combined W-band power amplifiers, sub-millimeter MMIC Schottky Varactor multipliers [15], and uses the MMIC GaAs membrane sub-harmonic mixer described to reach frequencies up to 1.8 THz.

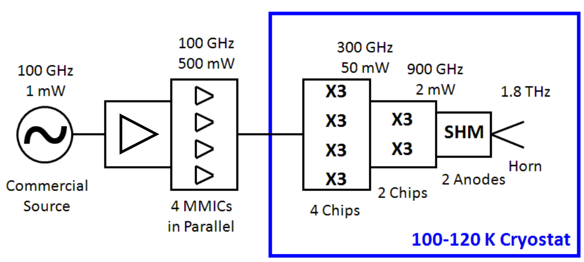

Fig.10. Proposed architecture for a 1.8 THz all-solid-state receiver chain. The LO chain is based on MMIC power-combined Schottky Varactor multipliers and power amplifiers, and uses the MMIC membrane sub-harmonic mixer described above.

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