A 520–620-GHz Schottky Receiver Front-End for Planetary Science and Remote Sensing With 1070 K–1500 K DSB Noise Temperature at Room Temperature

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***Abstract*—A state-of-the-art 520–620-GHz receiver front end working at room temperature was designed, built, and measured. The receiver front-end features a GaAs-Schottky diode-based subharmonic mixer and a 260–307-GHz doubler, both fabricated with the new LERMA-LPN Schottky process on a 4-μm-thick GaAs membrane suspended in a waveguide with metal beamleads. Small-area mesas and optimized transmission lines with low dielectric loading are used. At 295 K ambient temperature, an average of 1284 K DSB receiver noise temperature was measured over the 520–620-GHz frequency range, including the 3.5–8.5-GHz IF chain loss. A record 1130 K minimum DSB receiver noise temperature at 557 GHz was measured. At 134 K ambient temperature, an average DSB receiver noise temperature of 685 K from 538 to 600 GHz was measured when correcting for the cryostat window loss. A minimum DSB receiver noise of 585 K was measured at an RF center frequency of 540 GHz. The 520–620-GHz receiver presented in this article allows an increase in the sensitivity of the JUpiter ICy Moons Explrorer-SWI instrument of about a factor of two compared with requirements. It will allow study of the Jovian system with particular emphasis on the chemistry, meteorology, structure, and atmospheric coupling processes of Jupiter and its icy satellites, thereby providing important data for the exploration of their habitable zones.**

***Index Terms*—Beamlead, JUpiter ICy Moon Explorer, membrane, receiver noise temperature, Schottky, sub-harmonic mixer, submillimeter wave instrument, Y factor, 600 GHz.**

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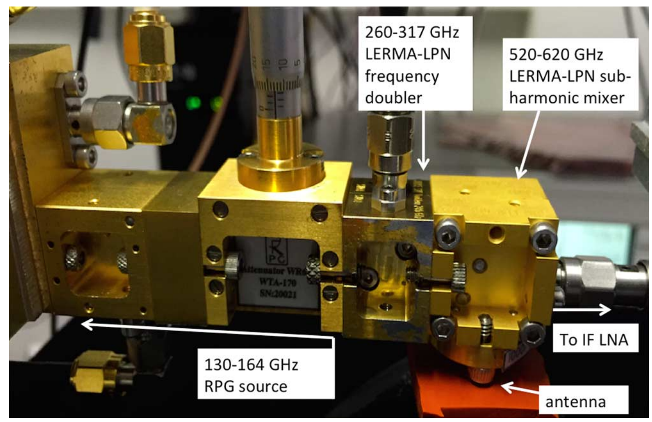

Fig. 1. 520–620 GHz compact receiver front end including the 520–620-GHz subharmonic LERMA-LPN mixer and the 260–317 GHz LERMA-LPN frequency doubler for the local oscillator of the SWI on JUICE [3].

I. Introduction

ABOVE 100 GHz, space-borne heterodyne receivers at submillimeter wavelengths offer the very high spectral resolution needed for atmospheric studies of the earth (e.g., cloud content, profile, quantification, and properties of ice particles [1]) and molecular spectral analysis of the temperature and composition of the atmospheres of other planets of our solar system, such as Jupiter and Ganymede [2]. The Submillimeter Wave Instrument (SWI) on the JUpiter ICy Moon Explorer (JUICE-L1 cosmic vision 2015–2025 program) consists of two heterodyne receivers working around 600 GHz and 1.2 THz, intended to observe both Jupiter and its icy moon atmospheres and surfaces. The receiver beams will be switched alternately to hot and cold loads for regular calibration. The radio frequency (RF) signal will be detected at mixer level and down-converted to 3.5–8.5-GHz intermediate frequency (IF) range and the data processed with CTS, CHS and ACS spectrometer systems. A spectrally pure local oscillator (LO) signal is necessary to accurately resolve the spectral lines. The 600-GHz and 1.2-THz front-end receivers incorporate compact, non-cryogenic Schottky diode-based solid-state devices for the mixer and last stage local oscillator frequency multipliers (see Fig. 1). The receiver circuit performance is driven by the circuit losses and the available LO power. In the 520–620-GHz receiver

TABLE I
STATE-OF-THE-ART OF SCHOTTKY MIXERS AND RECEIVER AT 600 GHz

Frequency (GHz)	DSB Receiver Noise Temperature T (K)	Ref (ambient temperature)
600 - BW 10%	2000 - 5000 (Mixer only)	Virginia Diodes Inc. (295 K)
530 - 610	1800 - 3000	[12] (295 K)
510 - 600	1500 - 2000	[11] (295 K)
520 - 620	1033 - 1713	This work (295 K)
520 - 620	540 - 1080	This work (134 K)

presented in this paper, a 260–307-GHz frequency-doubler fabricated using the LERMA-LPN Schottky process was previously demonstrated for the JUICE-SWI program [3]. Consequently, the development presented here focuses on the optimization of the system noise temperature performance, and more particularly on the 520–620-GHz mixer and IF transition circuits. The development of the LERMA-LPN 520–620-GHz subharmonic mixer will be described in the first part of the article, including circuit design and fabrication processes. The DSB noise temperature measurement of the full receiver chain including local oscillator source and IF back-end will be presented in a second part.

II. Mixer and Doubler Development

From 100 GHz and above, receiver microwave designs are commonly limited by substrate mode effects, and therefore the circuits are often built in waveguide structures where low loss can be achieved at high frequencies [4], [5]. Up to 300 GHz, quartz substrates can be used with flip-chip-mounted Schottky diodes; for example, a design with recorded state-of-the-art 700 K mixer noise temperature was reported in [6]. Above 300 GHz, the line loss starts to be significant enough to overcome the RF coupling and available local oscillator power. GaAs membrane-based monolithic integrated circuit technology offers very low loss and precise mounting with state-of-the-art performance up to 1.2 THz [7] and 2.5 THz [8]. Table I gives the state-of-the-art Schottky-based receivers recorded in the literature as compared to this work. For the 520–620-GHz mixer development, a preliminary mixer configuration analysis is conducted to define optimum dimensions of the membrane and channel, transmission lines, and the corresponding fabrication steps. Then, the diode geometrical cell dimensions are optimized using a 3-D EM simulator, Ansys' HFSS, and a harmonic balance simulator, Agilent' ADS. Finally the matching circuit is optimized to minimize conversion loss and mixer noise temperature. Great care is taken in designing the split-block package and the IF matching circuit. Each development and its corresponding fabrication is described in the following sections.

A. Mixer Configuration and Transmission Line Study

At 600 GHz, different membrane circuit topologies were explored, and the preferred choice is the sub-harmonic mixer, either in balanced [11] or antiparallel [12] configuration, allowing use of a local oscillator signal at half the RF frequency. An anti-parallel configuration was chosen for the LERMA-LPN 520–620-GHz receiver mixer. This configuration allows us to widen the width of the channel and to connect it to a low-impedance low-loss suspended GaAs membrane line coupled to waveguide using gold beamleads compatible with the LERMA-LPN process. The suspended line dimensions are optimized in HFSS to minimize losses at RF and LO frequencies. The dimensions are also defined to ensure that the RF and LO signals are propagated on the quasi-TEM mode, and that no unwanted transmission mode coupling occurs. In our case, the channel dimensions are limited by the cutoff frequency of the first higher mode that could be coupled from the incoming TE_{10} mode through the LO probe. In addition, air-gaps such as used in [9] help to reduce the high impedance line losses caused by dielectric loading of the suspended line channel. Gold beam-leads are necessary to suspend the membrane in the waveguide, and they permit very precise grounding and impedance definition of the line. On the other hand they tend to decrease the channel width and increase the line losses by few percent. Positioning of the beamleads is chosen where the impact of the mounting is the most significant, in our case at the probe junctions. The transmission lines developed for the mixer RF and LO matching circuits feature three low (40 Ω), medium (135 Ω), and high (140 Ω) impedance lines with respectively 400, 800, and 1300 dB/m loss at the RF frequencies, and around 40 Ω, 135 Ω and 170 Ω and 300, 520 and 900 dB/m losses at the LO frequencies.

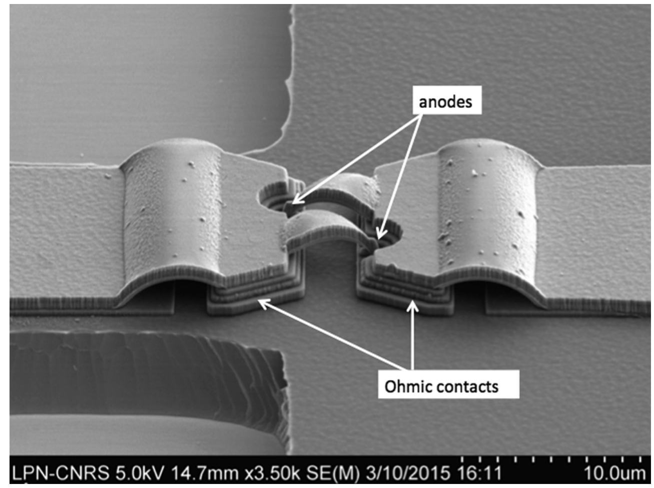

Fig. 2. Close-up of the 520–620-GHz subharmonic mixer diodes in an antiparallel configuration.

B. Definition of the Diode Cell

1) Optimization of the Diode Cell: The anode zero junction capacitance and the diode cell geometry, including anodes positions were optimized using the harmonic balance and optimization routines of ADS to minimize mixer conversion loss. The standard diode model customized in-house was implemented together in ADS with its close 3D passive environment, plus ideal input and output matching networks. A set of several iteration allowed us to find an optimum diode structure, where diode mesa-to-mesa and finger-to-finger distances are optimized below tens of microns to limit diodes parasitic coupling, such as pad-to-pad capacitance and finger inductance. The final sub-harmonic mixer cell is illustrated in Fig. 2. It features a pair of planar Schottky diodes integrated with the passive microstrip circuit onto a 4-μm-thick and 160-μm-wide GaAs membrane as discussed in the previous section. The electrical parameters of the LERMA-LPN Schottky diode model considered in the simulations are extracted from previous junction measurements: a series resistance Rs $= 32\ \Omega$, an intrinsic zero voltage junction capacitance of Cjo $=$ 1.1 fF, a saturation current Isat $=$ 0.14 fA, an ideality factor $\eta = 1.3$, and a built-in potential Vbi $=$ 0.8 V.

2) Mixer and Multiplier Diode Cell Fabrication Process: The LERMA-LPN novel fabrication process makes use of electron beam lithography combined with conventional epitaxial layer design, similar to that described in [10]. The epitaxial layers are grown locally by MBE (Molecular Beam Epitaxy) on a semi-insulating 500-μ-thick GaAs substrate. A 300-nm-thick AlGaAs layer is grown, followed by 3–5 μm of semi-insulating GaAs and 50-nm AlGaAs. The active diode structures consist of a 700-nm highly doped n+-GaAs layer (5.10^{18} cm^{-3}) and a 55-nm n-GaAs layer (3.10^{17} cm^{-3}) for the 520–620 GHz and a 350-nm n-GaAs layer (1.10^{17} cm^{-3}) for the 260–307-GHz frequency doubler. In the mixer case, the epilayer thickness is minimized to reduce the diode series resistance. The diode mesa is defined by a chlorine-based inductively coupled plasma (ICP) process, which gives a smooth vertical etch profile 2. Ni/Ge/Au/Ni/Au metal films are successively evaporated on the highly doped n+-layer and rapidly annealed in order to form the ohmic contact. The Ti/Pt/Au Schottky anodes are formed on the n-type layer. The gold air-bridge connection is formed using reflowed LOR resist.

C. Circuit Optimization and Fabrication

The considerations described in the previous two paragraphs have to be used as a tradeoff with the mixer optimization goals, i.e., mixer IF conversion loss and noise temperature, both related to the RF and LO signal coupling to the diodes.

1) Matching Networks Optimization: The methodology again uses a combination of nonlinear multi-harmonic circuit simulations (Agilent ADS) and 3-D electro-magnetic simulations (Ansoft HFSS) that is based on the methodology presented in [6]. First, the diode cell and the transmission lines are optimized as defined in the previous paragraph. RF and LO matching is achieved using a combination of the waveguide probes and series sequences of lines of the three impedances described earlier. The S-parameters of transitions between the lines of different impedances as well as the waveguide probes are calculated in HFSS with appropriate boundaries, waveports assignment, and de-embedding planes. S-parameter matrices and their attenuations, impedances, and permittivity values at central guided frequencies are then imported into ADS to optimize the line length in a global non-linear optimization. During this optimization step, ideal $\lambda/4$ initial lengths are given in the step-impedance filter and matching network in order to converge to optimum lengths of the circuit transmission lines. The low impedance lines are preferred for lowering the losses, however high impedance line are required to achieve good RF and LO coupling to the anodes. Finally, the dimensions found during the previous steps were fed back into the HFSS model to build the full mixer circuit structure shown in Fig. 3, and then simulated with the harmonic balance routine to confirm the mixer conversion losses and RF and LO signal coupling.

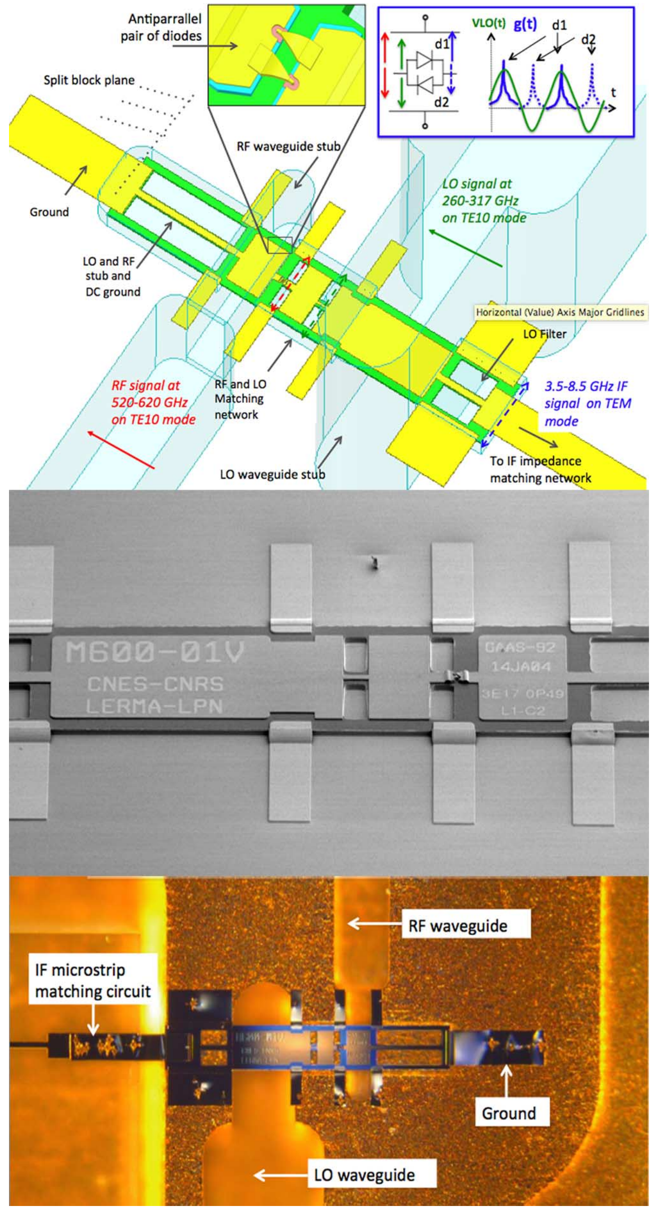

Fig. 3. Top: 3-D EM model 520–620-GHz subharmonic circuit. The circuit features two Schottky anodes in an anti-parrallel configuration, optimized mesa and finger dimensions integrated on a very thin GaAs membrane. The circuit is suspended in a wide channel with beamleads located at the IF grounding and the RF and LO probe interfaces. Middle: un-released 520–620-GHz subharmonic circuit fabricated on GaAs wafer. Bottom: 520–620-GHz subharmonic circuit mounted on the half split-block before measurement.

Finally a fabrication yield analysis was conducted taking into account a $+/-10\ \mu$m mounting precision and a variation of 20% in the diode junction capacitance. The final mixer circuit was simulated at IF frequencies going from 3.5 to 8.5 GHz and included into the harmonic balance simulations. An optimization loop was performed to define the optimum diode impedance value at IF frequencies: 250 Ω, corresponding to 500 Ω per anode appears optimum. A seven-step quarter-wavelength uniform response filter was designed to match the IF output to 50 Ω. Intrinsic transmission losses below 0.3 dB are predicted from 2.5 to 10 GHz in the 3D-EM simulation.

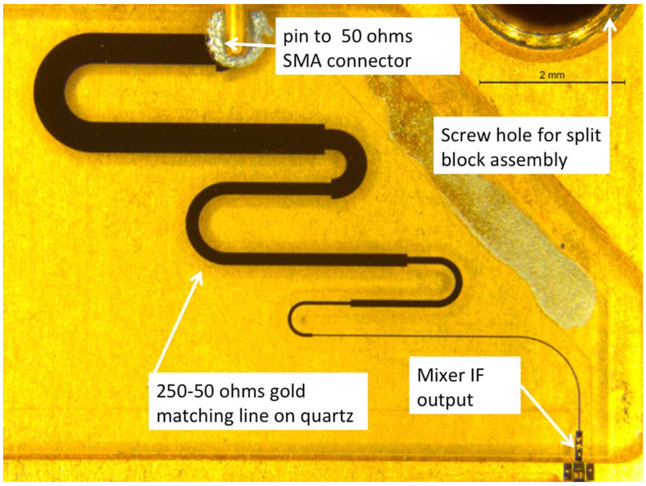

Fig. 4. The 3.5–8.5-GHz IF circuit mounted in its split block. The circuit features thick gold lines integrated on a 300-μm-thick quartz substrate.

2) Circuit Fabrication Process: The membrane thickness is minimized to reduce the dielectric losses. After complete formation of the diode cell and transmission lines, the whole device is protected with silicon nitride deposited using plasma-enhanced chemical vapor deposition (PECVD). Then the circuits are separated from each other by HBr-based ICP etching, and the beamleads are formed. The beamlead is attached a few micrometers from the side and on a distance below tens of micrometers. The final fabricated circuit on wafer is illustrated in Fig. 3. As a last step, the circuit is protected with photoresist and thinned down to the desired thickness by chemical wet etching. The IF matching circuit (in Fig. 4) line dimensions are designed to be readily fabricated; it is based on a 300-μm-thick quartz substrate, and the minimum line width is 25 μm. In Fig. 4 it is suspended in the block by being epoxied on its edges to avoid air bubbles below the substrate that could add unwanted modes and degrading performance. The line is folded to fit the block dimensions and its 1.7-μm gold plating thickness minimizes skin-effect losses.

3) Circuit Mounting: The mixer positioning in the block illustrated in Fig. 3 was chosen to minimize RF waveguide lengths for low loss to the extent allowed by the flange interfaces. The LO/RF waveguides, the microstrip channel and the IF connector socket were milled into two split metal block halves, with a calibrated mechanical precision of 10 μm. The mixer and IF circuits are manually mounted and connected together by bondwire inside the lower half of the waveguide cavity. The manufacturing of the block was done by the SociétéAudoise de Précision. The 520–620-GHz mixer block has been assembled at the Observatory of Paris using techniques that are readily space qualified.

III. 520–620-GHz Receiver Noise Temperature Measurement at 295 and 134 K

A. Local Oscillator Chain

The local oscillator signal used for the 520–620-GHz receiver measurement was generated by a chain composed of multiplier and amplifier stages that was specially designed and built for the SWI. A 21.7–25.6-GHz signal from an Agilent signal generator was tripled and amplified at the E-band and then fed to a cascade of two frequency doublers. The E-band tripler-amplifier and 130–154-GHz doubler modules were developed by Radiometer Physics GmbH. The last stage 260–307-GHz frequency doubler was designed and fabricated at LERMA-LPN (see Fig. 5). This multiplier features four anodes in a balanced configuration monolithically integrated on a 5-μm-thick GaAs membrane circuit similar to that used for the mixer. A conversion efficiency of about 15%–22% was measured in the 260–307-GHz band, which is in very good agreement with simulations [3]. A lifetime test over more than 1600 h of continuous RF operations with 45 mW of input power has been successfully recorded at LERMA-LPN.

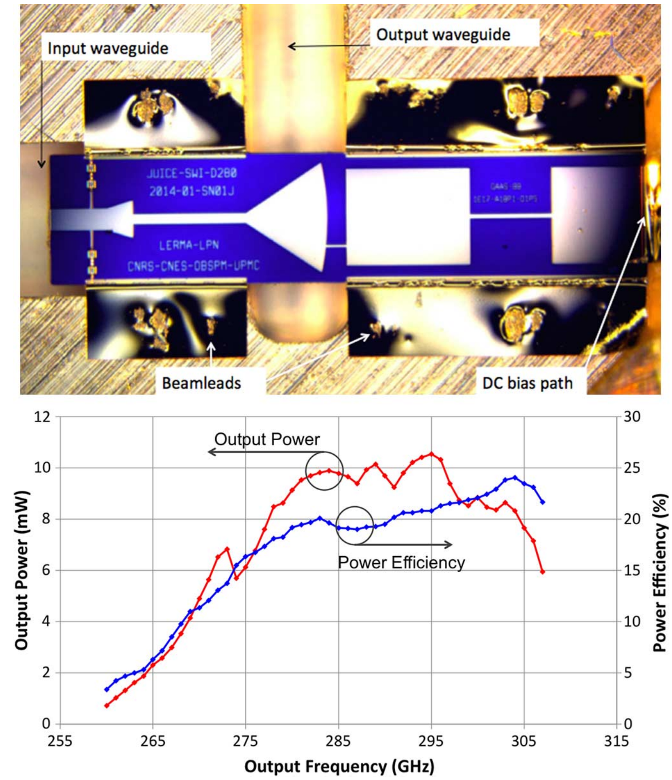

Fig. 5. Top: 260–307-GHz doubler for JUICE-SWI: circuit mounted in the block. Bottom: measured output power.

B. Y-Factor Measurement Bench and Results at 295 Kelvins

The setup, illustrated in Fig. 6, is mounted on an optical table and uses multiple opto-mechanical parts from Newport to hold the mixer, LO chain and the IF amplifier chain to the bench. The first IF low noise amplifier is a Miteq 4–8.GHz LNA with NF $\leq$ 0.7 dB. Two matched loads at physical temperatures of $T_{hot} = 293.25$ K and $T_{cold} = 77$ K are presented alternately at the input of the receiver. The output powers $Pout_{Thot}$ and $Pout_{Tcold}$ are used to calculate the Y factor for each measurement point. The LO power was optimized for best noise in the 4–8-GHz band and is 3 mW in average. The double-side-band receiver noise temperature over RF frequency is measured with an Agilent N1912 power meter with E9300A power sensor. The receiver front-end was tested in air at room temperature. The optical path from the liquid-nitrogen-cooled calibration target

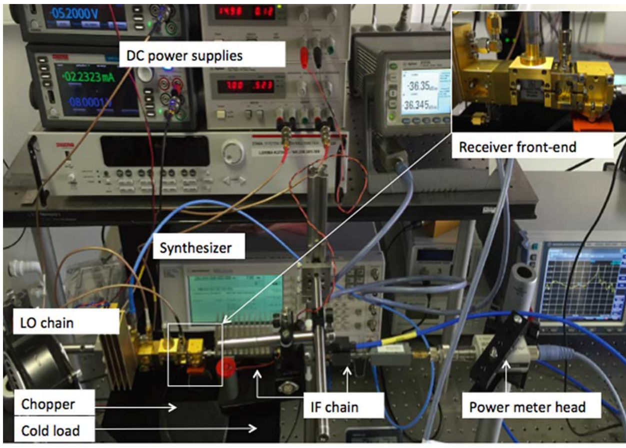

Fig. 6. Photograph of the 520–620-GHz receiver noise temperature measurement bench at 295 K ambient temperature including the 520–620-GHz subharmonic LERMA-LPN mixer and the 260–317-GHz LERMA-LPN frequency doubler for the local oscillator of the SWI on JUICE [3].

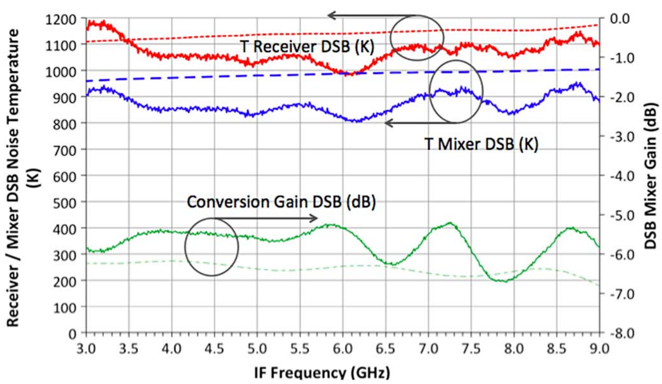

Fig. 7. DSB receiver noise temperature at an RF central frequency of 557 GHz at room temperature as a function of IF frequencies with 3 mW of local oscillator power. The measurement are solid lines and simulations are shown by dashed lines.

to the mixer was 6.5 cm. The humidity was 44%. Without any correction for water vapor absorption, less than 1500 K receiver double-side-band (DSB) noise temperature was measured for LO frequencies ranging from 264 to 307 GHz, corresponding to RF frequencies ranging from 520 to 622 GHz, including IF offsets. A minimum of 1130 K receiver DSB noise temperature was measured at an LO frequency of 268.5 GHz corresponding to an RF center frequency of 557 GHz. Additional measurements were made in the laboratory at 557-GHz RF center frequency with a Rhode and Schwarz FSV 40 GHz spectrum analyzer over the IF bandwidth (2–9 GHz) with a resolution of 10 MHz and with humidity of 31%. The recorded performances are an average DSB receiver noise temperature of 1070 K, a mixer average DSB noise temperature of 872 K and a mixer average DSB gain of -5.7 dB for IF frequencies ranging from 3.0 to 9.0 GHz (see Fig. 7).

C. Y-Factor Measurement Bench and Results at 134 Kelvins

The receiver was mounted on a cryostat cold plate as illustrated in Fig. 8. The room-temperature LNA from Miteq was replaced by a low-noise factory LNFLNC1 12A 1–12GHz cryogenic amplifier optimized to work at 12 K ambient temperature.

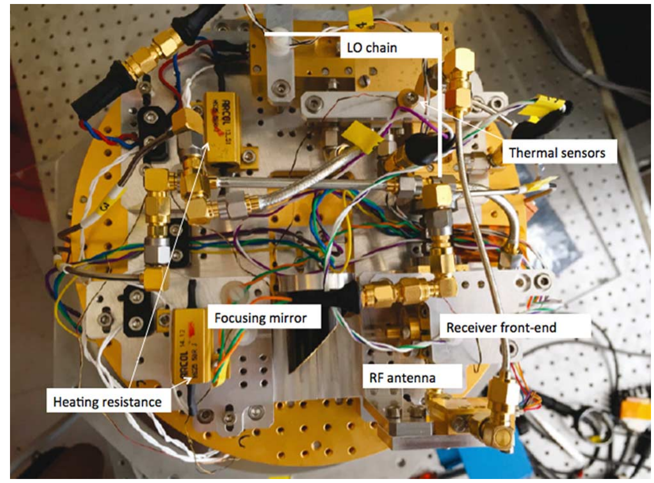

Fig. 8. Photograph of LERMA 600-GHz Schottky receiver mounted on the cold plate of a cryogenerator used to measure its equivalent noise temperature at 134 K. The 140-GHz LO chain is thermally insulated from the 260–307-GHz frequency doubler and 520–620-GHz subharmonic mixer and is maintained at 240 K.

A custom two-stage intermediate plate was designed to cool down both the 260–307-GHz doubler and the mixer to 134 K, while keeping the 140-GHz LO chain at 240 K. The temperatures were monitored with $+/-1$ K accuracy. A gold-plated 90° off-axis parabolic mirror with an effective focal length of 25.4 mm and a diameter of 25.4 mm was used to focus and direct the RF beam through the cryostat window with minimum RF loss. The cryostat window was made of a 2-mm-thick HDPE disk and two 250-μm-thick Zitex G110 IR layer filters. The HDPE disk was tilted by 15° from normal to the incident RF beam in order to decrease standing waves. The liquid-nitrogen-cooled cold calibration target was hand-held as close to the window as possible to minimize the optical path in air to 3 cm. This target had a small reservoir of liquid nitrogen that kept the temperature of the calibration target close to 77.4 K. No correction was made for atmospheric RF losses due to the 3 cm of optical path in air from the cryostat window to the calibration target. However, the cryostat window RF loss was measured to be 5% at 600 GHz, and this was used to correct the raw data. Fig. 9 shows the DSB receiver equivalent noise temperature versus RF center frequency at 134 K ambient temperature. The average DSB receiver noise temperature was measured at 685 K from 538 to 600 GHz when correcting form the cryostat window losses, with a minimum DSB receiver noise of 585 K at 540 GHz RF center frequency. Further measurements are planned, including LO power sweep and its impact on the system dc power consumption.

IV. Retro-Simulations at 295 K and 134 K

After fabrication and wafer release, the diodes of the 600-GHz subharmonic mixer were characterized at direct current in order to use the series resistance Rs, the saturation current Isatand the ideality factor η in a set of experimentally customed retro-simulations using the standard ADS model. Additionally, a Monte Carlo simulation that takes into account the geometry of the anode was also used to extract the intrinsic zero voltage junction capacitance Cjo at 295 K and

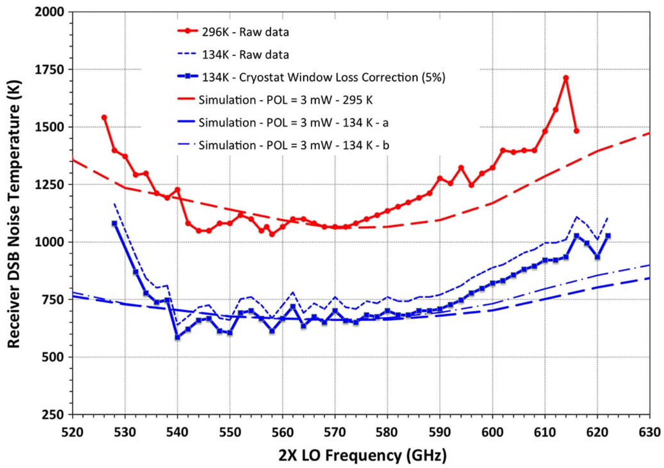

Fig. 9. Diagram of 520–620-GHz DSB receiver noise temperature at 295 K and 134 K ambient temperature as a function of RF frequency. The receiver retro-simulations are in dot-lines.

134 K. Finally, the Schottky junction built-in potential Vbi was found by interpolating the measured I–V curve with the temperature-dependent analytical equation from [14]. Two main sources of noise are included in the retro-simulations: the thermal noise generated generated by the thermal agitation of the charge carrier in the series resistance and the shot noise of random fluctuations of the electric current in the barrier. The hot-electon noise is not modelled in this case, therefore the simulation results are expected to be in accordance with the experimental results only for low local oscillator power of $\leq$3 mW. Both 295 K and 134 K retro-simulations as a function of RF frequency are shown in Fig. 9. At 295 K, the values are Rs $=$ 35 Ω, Cjo $=$ 1.22 fF, Isat $=$ $1.6 \cdot 10^{-12}$ A, $\eta = 1.3$ and Vbi $=$ 0.718 V. At 134 K, the Cjo was defined with the physical Monte Carlo simulation, and the four remaining diode parameters Rs, η, Isat, and Vbi were obtain solely by interpolating the model I–V curve with the temperature-dependent analytical equation from [14]. A temperature scaling factor was added in the ideality factor of the standard ADS diode model in order to obtain a temperature dependency in the exponential function. At 134 K, two set of parameters are defined for the retro-simulations (curves a and b) with: Rs $=$ 35 Ω (curve a), Rs $=$ 32 Ω (curve b), Cjo $=$ 1.19 fF (curve a and b), Isat $=$ $1.6 \cdot 10^{-12}$ A (curve a), Isat $= 6 \cdot 10^{-16}$ A (curve b), $\eta = 2.8$ (curve a), $\eta = 3.2$ (curve b), and Vbi $=$ 0.792 V (curve a and b). Supplementary measurement of the diodes I–\V curves are planned at 134 K to confirm the diode parameter values (Rs, Isat, and η) and proceed with a retro-simulation procedure similar to the one done at 295 K.

V. Conclusion

A state-of-the-art 520–620-GHz receiver front end working at room temperature (298 K) has been developed with the new LERMA-LPN process. This performance is achieved by optimizing the critical dimensions of the mixer (active layer thickness, diode dimensions and matching network transmission lines) and the receiver interfaces (mixer block and IF backend). Its recorded performances fulfill the very high spectral resolution science requirements for the JUpiter ICy Moons Explrorer-SWI. In particular, it will permit measurement of the temperatures and wind fields in Jupiters stratosphere with accuracy improved by a factor of 2 over what was originally envisaged, providing enhanced constraints on the circulation regime in this part of the atmosphere. Similarly, the spatial and vertical distribution of the Galilean moons atmospheres will be characterized more accurately than initially proposed, with implications for a better understanding of the ultimate sources for these atmospheres (sublimation, sputtering, etc.).

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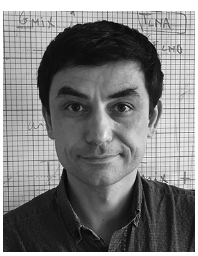

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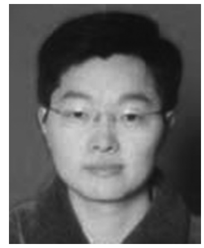

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