SWI 1200/600 GHz highly integrated receiver front-ends

SWI 1200/600 GHZ HIGHLY INTEGRATED RECEIVER FRONT-ENDS

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS
6-9 OCTOBER 2015

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ABSTRACT

The band 1 (530-625 GHz) and band 2 (1080-1275 GHz) subharmonic receiver front-ends for the submillimeter wave instrument (SWI), which is part of the European Space Agency (ESA) Jupiter Icy moons Explorer (JUICE) class-L mission, are currently being developed by Omnisys Instruments AB. The front-end prototypes for the two band 1 receiver channels, which is the current instrument baseline, comprise a subharmonic Schottky diode terahertz monolithically integrated circuit (TMIC) mixer, and a module integrated intermediate frequency (IF) InP HEMT MMIC cryogenic low noise amplifier (LNA) design from Low Noise Factory, fabricated at Chalmers University of Technology. Measurements show a typical room temperature performance of ~1500 K double sideband (DSB) with a minimum receiver noise temperature of around 1100 K. The receiver front-end module is operated with only 1-2 mW of local oscillator power over the full band and has a total power dissipation of below 40 mW with about 30 dB of conversion gain.

The band 2 receiver front-end which is currently not baseline for SWI and under development, is based on a scaled band 1 mixer design with the option of applying a forward bias of the mixer diodes. The band 2 front-end module also comprises an integrated spline horn antenna with a simulated Gaussian efficiency of better than 95% over 20% bandwidth. Moreover, for minimizing LO losses and controlling the LO standing waves, a 600 GHz Schottky diode varactor X2 multiplier TMIC, with an estimated conversion efficiency of 15-20%, is integrated into the front-end receiver unit. The 600 GHz doubler performance estimate is based on a breadboard doubler with simulated 10% bandwidth and measured output power of excess 4 mW with over 15 % of peak conversion efficiency.

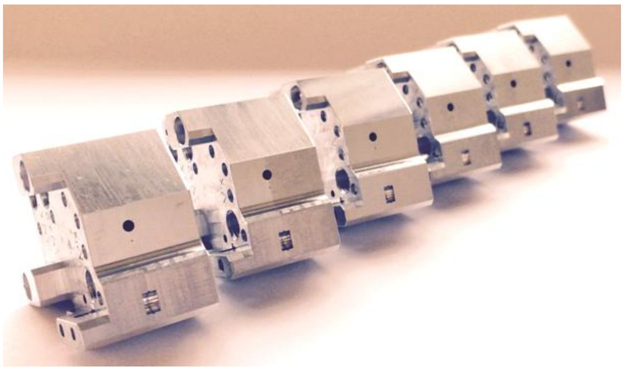

Figure 1. SWI band 2 integrated receiver front-end prototypes with integrated smooth wall spline horn antenna.

1. INTRODUCTION

Omnisys Instruments responsible for the development of the two band 1 broadband 530-625 GHz receiver front-ends (current SWI baseline), the continuum channels used for polarimetric surface observations and the fast line survey Auto Correlator Spectrometer (ACS) back-end with 4 GHz bandwidth and 20 MHz spectral resolution in low power operating mode. Thereto upon direct request by the European Space Agency (ESA), Omnisys has been assigned a contract for the development of a band 2 spectrometer prototype with a tuneable local oscillator covering the 1080 GHz to 1275 GHz frequency range. In this context the current status of Omnisys 600/1200 GHz front-end receiver development for the SWI instrument is presented, including a technology overview and detailed system design.

The Submillimetre Wave Instrument (SWI) is part of the JUpiter ICy moons Explorer (JUICE) mission [1], which is the next large European science mission planned for launch in 2022 and arrival at Jupiter in 2030. The spacecraft will spend at least three years studying the chemistry of Jupiter's stratosphere as well as the atmospheres of the three largest moons, Ganymede, Callisto and Europa. It will also study the moons' surfaces and thermo-physical properties.

The integrated receiver modules are based on state-of-the-art passively cooled GaAs Schottky diode mixer and multiplier Terahertz Monolithically Integrated Circuits (TMIC's) [2, 3] and cryogenic IF InP HEMT LNA MMIC's [4] fabricated at Chalmers University of Technology, ensuring both a low power consumption and an ultra-low noise response. The band 2 receiver package is in particular interesting as it is designed to not only harbor the IF LNA but also include the last stage 600 GHz multiplier TMIC as well as a high performance smooth walled spline horn [5]. The close integration of front-end components as well as co-modeling impose an interesting challenge from both a technology and packaging perspective, however is crucial for achieving the best system performance possible at THz frequencies. In addition it eases the overall instrument design allowing for a larger flexibility during the instrument optical and receiver sub-system development phase.

2. FRONT-END RECEIVER DESIGN

The band 1 receiver units have been designed so that two identical receiver unit chassis can be used, one for each polarization, which is the baseline configuration of SWI (2x band 1 V/H). The re-use of identical mixer chassis for both V/H channels is made possible by introducing a 45 degree waveguide twist in the RF path which will be realized in the external antenna design. One of the receiver units also has to be mounted up-side-down on the receiver baseplate. Moreover the IF LNA and a constant current biasing circuit has been integrated to the modules together with an internal mixer matching network minimizing the IF standing waves. The integration of the LNA provides a sound thermal environment, but also eliminates the IF connector interfaces which are a known source for potential pick up of EMI. Thereto all bias interconnects use shielded semi-rigid cables.

The band 2 receiver has been designed to also include a smooth walled spline horn antenna and the 600 GHz X2 multiplier. This is done in order to minimize waveguide transmission and interface losses, and to reduce the effects of RF and LO standing waves.

The horn antenna has been designed to meet the SWI optical requirements (optical system design by IAP, Bern) and the receiver module interfaces have been optimized together with the SWI team.

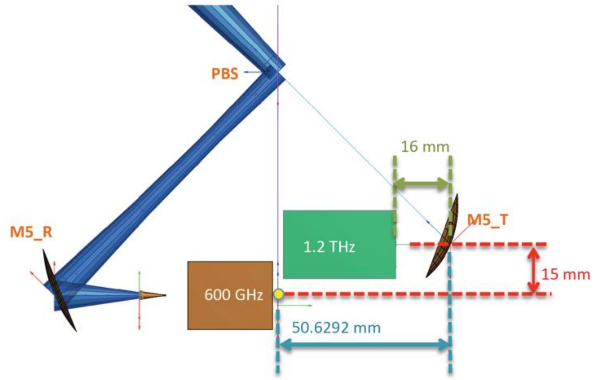

Figure 2. The SWI reflector system showing the relative position of the band 2 receiver unit relative the current band 1 receiver unit. Courtesy of Hyunjoo Kim, IAP, Bern.

The main requirement for the horn was that the beam waist radius should be 0.4326 mm with the beam waist located 16 mm from the first mirror, displaced 15 mm towards the optics side compared to the band 1 receiver unit. Thus the band 2 footprint of the mixer becomes squeezed in from all sides leaving very little room for the bias and IF connectors and other necessary infrastructure, e.g. thermal strap mounting holes, baseplate alignment holes, standard LO flange interface etc. In summary the band 2 receiver prototype unit design converged into an E-plane splitblock with miniature vertical SMP connectors for the bias interconnects and with two of the LO waveguide interface flange screws left out.

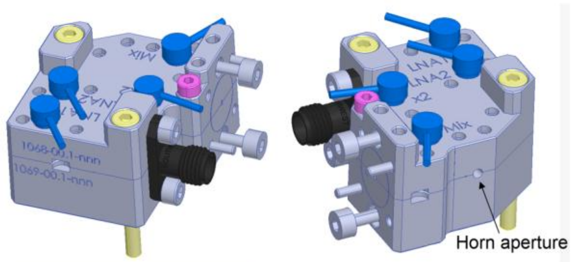

Figure 3. CAD model of the Band 2 front-end receiver unit with module integrated horn antenna, mixer, IF LNA, 600 GHz X2 multiplier and internal individual bias circuits for the LNA, mixer and multiplier.

The simulated nominal performance based on realistic 3D-EM modelling using Ansys HFSS in combination with Harmonic Balance simulations in ADS are presented below. An optimum conversion loss of about 10 dB is reached at 2 mW of LO drive, which is about 2 dB higher compared to the band 1 mixer design.

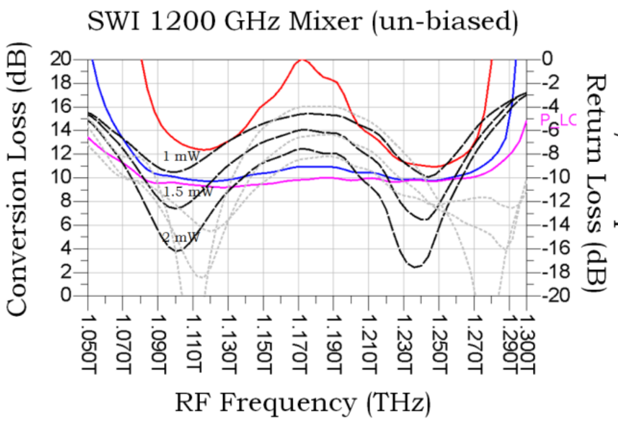

Figure 4. Simulated band 2 unbiased mixer performance.

The smooth walled spline horn antenna is designed using a mode-matching software CORRUG in combination with an iterative Matlab optimization script for calculating the far-field pattern. The Gaussian efficiency was optimized to be higher than 95% over the entire band.

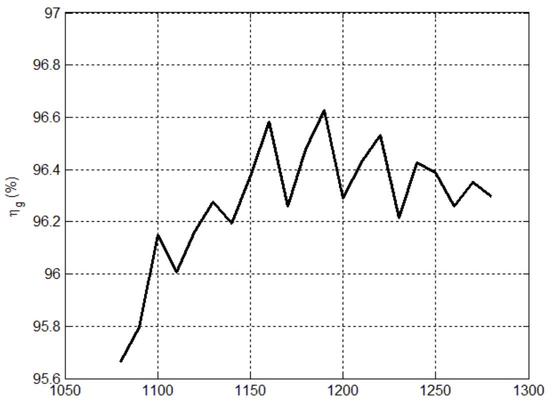

Figure 5. Simulated Gaussian efficiency of the smooth wall spline horn design versus frequency in GHz.

To verify the 600 GHz doubler performance a separate 600 GHz module is first designed and tested. Below the breadboard 4-anode and 2-anode doubler TMIC's are shown.

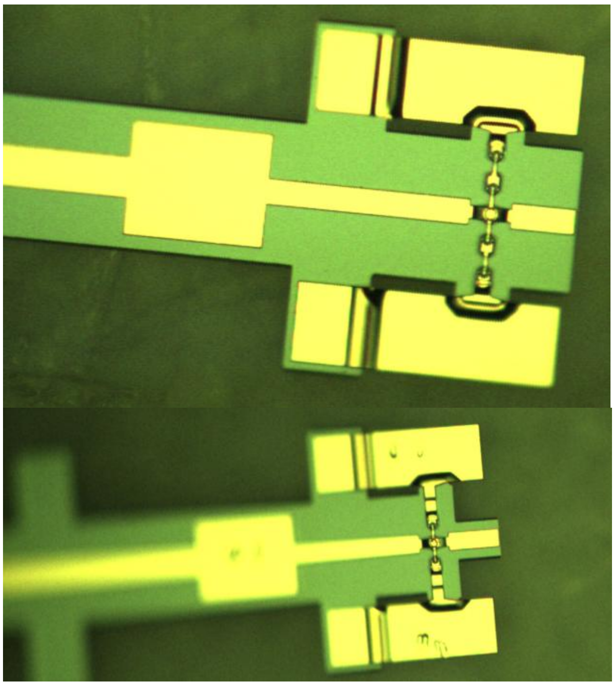

Figure 6. Photograph of the developed 4-anode (top) and 2-anode (bottom) 600 GHz X2 breadboard multiplier TMIC's with excess 4 mW of output power.

The simulated performance of a new improved 600 GHz doubler design optimized for 10 mW of input power is compared to the simulated breadboard high power doubler design at 30 mW of input power. As can be seen the efficiency has been improved by on average 5 %, and the full bandwidth of the band 2 is covered with better than 15 dB of input return loss.

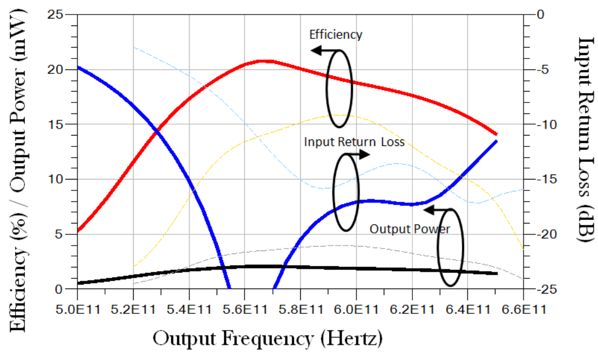

Figure 7. Simulated performance of the new improved 600 GHz doubler (solid) at 10 mW of pump power compared to the high power breadboard doubler (dashed) at 30 mW of input power.

3. TESTSETUPS

For initial testing of the receivers in room temperature a benchtop frequency independent Y-factor optical test-setup has been designed and verified in GRASP for the 100 GHz to 1300 GHz range. The optics are designed for minimum spillover using oversized focusing mirrors, a plane switching mirror, and at least one ambient and one thermally regulated hot conical load from TK Instruments originally developed for ALMA with a design frequency range from 30 GHz to 950 GHz.

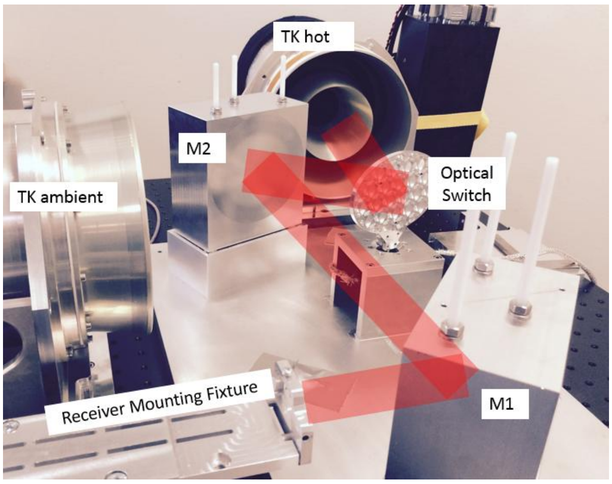

Figure 8. Room temperature Y-factor setup.

In parallel a general THz cryogenic testsetup is under development which will allow tests of the entire receiver chain in vacuum and at different temperatures. The cryostat is based on a dewar originally developed for the VLBI2010 front-end system and consists of a 2-stage turbo charged cooler from Sumitomo Heavy Industries Ltd, with a cooling capacity of around 35 W and 5.5 W for the 70 K stage and 20 K stage respectively. The setup will use internal loads based on miniature TK-ram absorbers from Tomas Keating, with active temperature regulation at around ambient temperature or cooled to ~70 K or ~30 K respectively. The optical path is switched using a cryogenic stepper motor with a focusing lens weighing only about 10 g designed for switching times down to 100 ms.

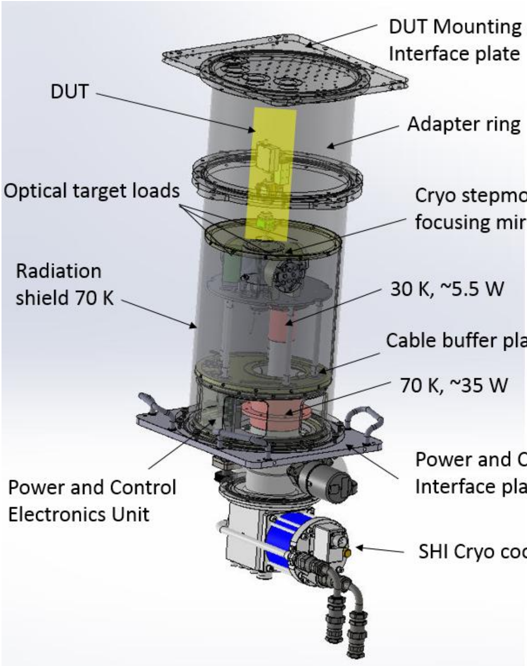

Figure 9. Cryogenic test setup under development.

For the first band 1 receiver tests a LO chain developed during the TERACOMP project has been used consisting of a W-band metamorphic HEMT multiplier and PA module from IAF followed by a high power HBV varactor tripler from Wasa Millimeter Wave AB with an output power of around 5 mW [2]. For initial tests of the 600 GHz breadboarding doubler a commercial 300 GHz high power source from Wasa Millimeter Wave with peak output power of 30 mW has been used. A photograph of the testsetup is shown below with a 600 GHz TMIC doubler module under test.

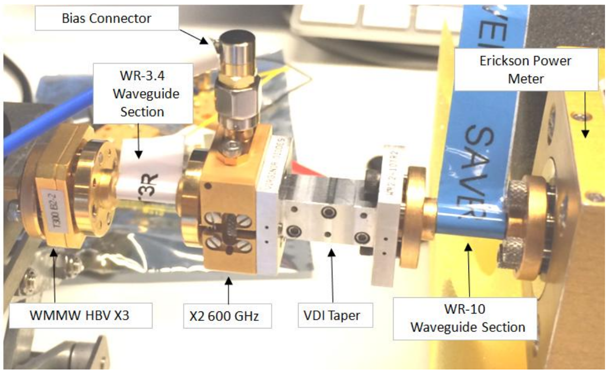

Figure 10. Photograph of the 600 GHz TMIC breadboard module under test using a 30 mW 300 GHz test source from Wasa Millimeter Wave AB.

4. RESULTS

Two different band 1 receiver units have successfully undergone full band characterization at IAP in Bern, both at ambient temperature as well as initial testing at

150 K. The latest receiver noise measurements at ambient temperature are presented below and compared to simulated room temperature receiver and mixer noise performance.

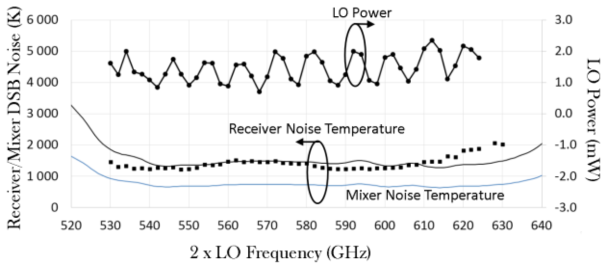

Figure 11. Measured band 1 receiver front end performance compared to simulations of the receiver and mixer noise performance versus LO frequency. Applied optimum LO pump power during measurements is also shown.

Two band 2 600 GHz breadboard doublers were tested at up to 25 mW of input power at ambient temperature with and without a 2” long waveguide section inserted between the 600 GHz doubler module input and 300 GHz testsource output. The results show on a strong but almost equivalent LO ripple response of the two modules pointing to excellent repeatability for the particular assembly. The peak output power for both modules was above 4 mW at an estimated efficiency of excess 15 %. The measured performance is well in agreement with simulations. The optimum bias was about 0.7 V lower on average compared to simulations indicating a small offset in the varactor model.

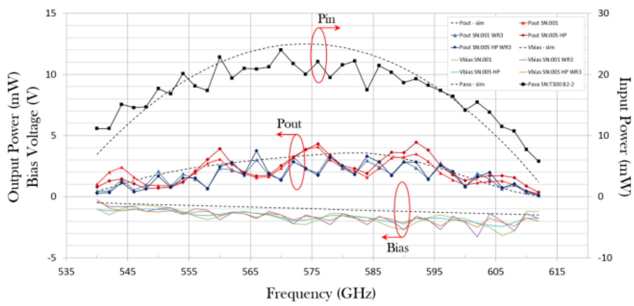

Figure 12. Measured and simulated performance of two band 2 600 GHz TMIC doubler breadboarding modules.

The design and build-up of an internal LO chain test setup at Omnisys is ongoing. This testsetup will consist of an E-band multiplier and PA from Millitech with a peak output power of 500 mW in the band center and 200 mW at the band edges. Three different high power narrowband low loss isolators from HXI are used to cover the full band, followed by two externally power combined 150 GHz band 1 doublers from Radiometer Physics Gmbh. A power combined high power version of the 150 GHz doubler for band 2 is currently under development by Radiometer Physics Gmbh as part of the SWI consortium, another alternative is to use a single chip high power doubler under development at ACST. The 150 GHz doubler stage is followed by a 300 GHz doubler from either LERMA (baseline) or Omnisys (backup), which also are under development. Different configurations of the specific LO chain components are foreseen as well as the use of a directional coupler for power monitoring at E-band.

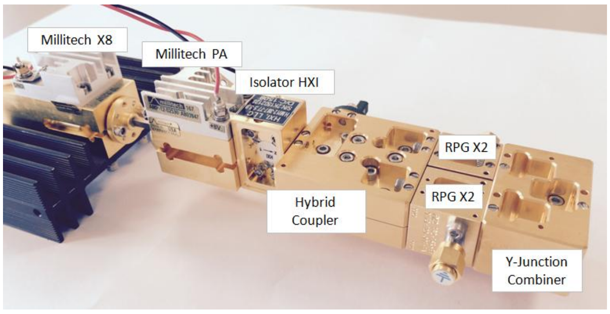

Figure 13. General LO testchain setup under development at Omnisys Instruments AB.

5. CONCLUSIONS

The SWI band 1 receiver front-ends are currently under development and characterization of the first prototypes indicate that a double sideband receiver noise temperature of below 1500 K is achievable at room temperature over the complete local oscillator bandwidth of 530 GHz to 625 GHz with less than 2 mW of local oscillator power, and that an improvement of ~200 K is expected on average when cooling the receivers to 150 K.

For band 2, which currently is not part of the instrument baseline, both the development of the broadband LO system and mixer are considered critical and both impose a great technological challenge. The main obstacles are the limited LO pump power (< 200 mW) at E-band in the current LO system architecture, implicating the need for the development of a biased subharmonic mixer. Secondly the impact of LO standing waves is considered critical, as observed in the band 1 LO chain development. One way of reducing the effect of LO ripple is to use the power combining doubler topologies throughout the entire LO chain. This can effectively reduce the standing waves as reflected power at the input is terminated in the hybrid coupler load however at the cost of increased complexity and higher insertion losses.

Based on the band 1 receiver front-end prototype performance there is a good chance that the band 2 requirements of a cooled (150 K) double sideband receiver temperature of below 3500 K can be reached.

Breadboard results on our high-power 600 GHz doubler indicate that achieving more than 15% of conversion efficiency is realistic over the band, which in turn points to that 15-20 mW of LO power has to be available at 300 GHz for an unbiased mixer topology to work. For the biased case, 1 mW of LO power is estimated to be sufficient for achieving optimum pump while maintaining reasonable noise performance. This would relax the power requirement to about 10 mW at 300 GHz which seems to be realistic in the current LO system architecture.

6. ACKNOWLEDGEMENTS

This work was carried out in the GigaHertz Centre financed by the Swedish Governmental Agency of Innovation Systems (VINNOVA), by the Swedish National Space Board (SNSB), and by the European Space Agency under contract 4000112396/14/NL/BW. The authors would like to acknowledge the SWI-team and in particular Hyunjoo Kim, Karl Jakob and Axel Murk with the Institute of Applied Physics IAP, University of Bern, for characterization of the SWI band 1 receiver and fruitful discussions regarding the band 2 receiver antenna design. We would also like to acknowledge master thesis student Hong-Xia for the work of designing the high power 600 GHz X2 breadboard multiplier, technician Mats Myremark for the excellent work of fabricating the high precision splitblock modules, and Ph.D student Robin Dahlbäck for assistance with the characterization of the 600 GHz breadboard doubler.

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