MMIC Schottky based receiver technology for the Submillimetre Wave Instrument –SWI- onboard EJSM/Laplace

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Abstract- **We present here the development of several sub-milllimetre wave heterodyne receivers based on MMIC Schottky diodes in the framework of the SWI instrument study for the ESA/NASA EJSM mission. First, a 560 GHz heterodyne receiver using MMIC Schottky devices has been developed by JPL. It features a 280 GHz tripler and 560 GHz sub-harmonic mixer integrated in a single block. It exhibits a DSB mixer noise temperature of 1400 K at 590 GHz. In parallel, a 664 GHz receiver featuring MMIC Schottky devices has been developed by RPG. It exhibits state-of-the-art performance with a DSB mixer noise temperature around 1550 K at 650 GHz. Finally, the 1200 GHz channel is under development at JPL. It features an LO source inherited from the HIFI project for the generating enough power at 600 GHz, and a novel 1200 GHz MMIC biasable sub-harmonic mixer that will be presented.**

I. INTRODUCTION

A Submillimetre Wave Instrument (SWI) has been proposed as a potential payload instrument of the Jupiter Ganymede Orbiter (part of the joint ESA/NASA EJSM proposal) [1]. The primary scientific objectives are to investigate the exchange mechanisms in the middle atmosphere of Jupiter by the remote sensing of key molecular species such as the water line at 557 GHz and the methane line at 1256 GHz. As a secondary objective, it would also investigate the exosphere/ionosphere dynamics and thermo-physical surface properties of Jupiter's moons. The proposed radiometric and spectroscopic instrument features two heterodyne channels as shown in Fig. 1, one centered around 560 GHz close to the water line, and another one centered around 1200 GHz close to the methane line.

Several R&D activities both in Europe and in the US have been engaged that are tailored for this instrument. The 600 GHz SWI channel has been investigated both in Europe and in the US. First, a 560 GHz receiver has been developed by JPL. It features a 280 GHz MMIC tripler and 560 GHz MMIC sub-harmonic mixer integrated in a single block. In parallel, a 664 GHz receiver has been developed by RPG. It uses a 332 GHz MMIC doubler and 664 GHz MMIC sub-harmonic mixer (SHM) based on European Schottky diodes. The design, fabrication and tests are presented. Finally, a 1200 GHz channel is under development at JPL. The receiver architecture is directly inherited from the HIFI project for the LO generation at 600 GHz. Using identical MMIC GaAs membrane process technology , a novel 1200 GHz MMIC sub-harmonic mixer has been designed, fabricated and is presented here.

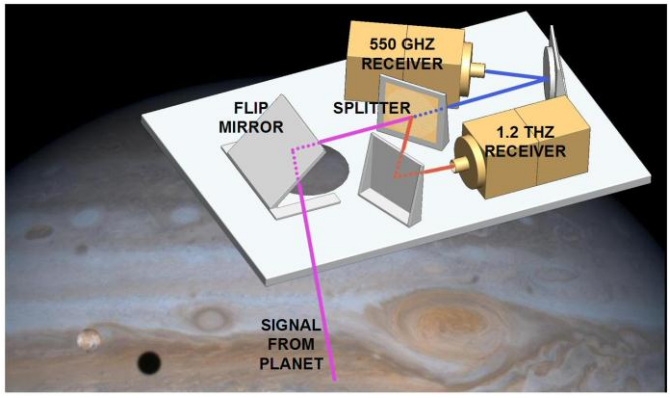

Figure 1: Schematic representation of the SWI front-end, including one heterodyne channel centered at 570 GHz, and another one at 1.2 THz.

II. 560 GHZ INTEGRATED RECEIVER DEVELOPMENT AT JPL

An integrated 560 GHz receiver front-end based on MMIC GaAs membrane Schottky diodes fabricated by the Micro Device Laboratory from JPL has been designed fabricated and tested. Both devices have been designed using a combination of 3D-EM simulations (HFSS from Ansys [2]) and linear/non-linear circuit simulations (ADS from Agilent [3]).

A. Design and fabrication

The 560 GHz receiver channel includes a 280 GHz MMIC tripler using 6 Schottky diodes in balanced series configuration, and a 560 GHz MMIC sub-harmonic mixer using a pair of balanced series Schottky diodes. A photo of the integrated receiver is shown in Figure 2.

The design procedure is as following: both the tripler and mixer components are first optimized independently to cover the desired frequency range and exhibit best performances, i.e. best efficiency for the tripler, and best sensitivity for the sub-harmonic mixer. Then the waveguide matching circuit in between these two components is optimized for best coupling efficiency at the desired LO frequency range which is 255 to 300 GHz.

The 280 GHz tripler is based on an earlier design from Maestrini [4]. Simulations have shown that the chip topology can be kept unchanged and only the waveguide structure is re-optimized to cover the 255-300 GHz band, instead of the initial 265-340 GHz bandwidth. The 560 GHz sub-harmonic mixer is "scaled" from an earlier design at 874 GHz [5], and is biasless. It is estimated that the tripler will output enough LO power (at least 3 to 5 mW estimated) to pump the sub-harmonic mixer.

During the design phase, it has been shown that integrating the last stage tripler together with the sub-harmonic mixer presents significant advantages: lower waveguide losses, lower standing waves between both devices as the entire tripler-mixer combination is optimized together, resulting in a flatter and lower pump power required at W-band, a tripler bias voltage quasi-constant over the frequency range, and less waveguide flanges interfaces required. As shown in Figure 3, only a single W-band UG387 flange is required for LO input, as well as an IF SMA connector. A diagonal horn centered at 560 GHz is integrated into the block for the RF coupling.

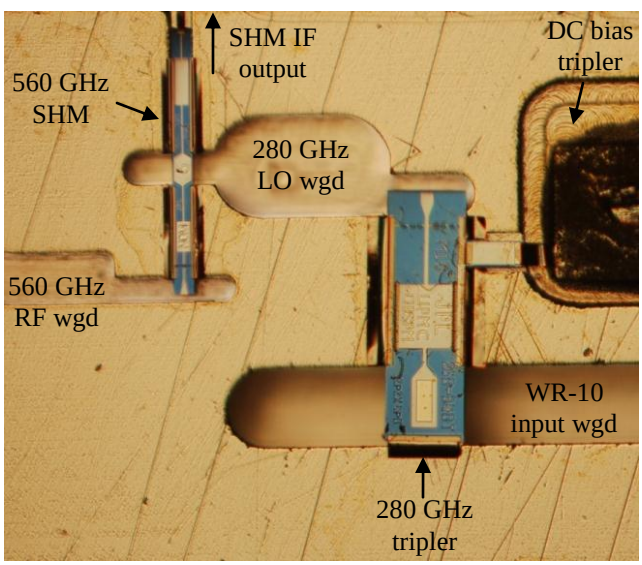

Figure 2: Integrated 560 GHz receiver from JPL, featuring a 280 GHz MMIC tripler and 560 GHz sub-harmonic mixer in a single cavity.

The integrated 280 GHz tripler and 560 GHz sub-harmonic mixer also includes a 2-11 GHz IF impedance transformer circuit and an output K-type glass bead connector. Further integration level is expected by including an IF pre-amplifier inside the block as a future step.

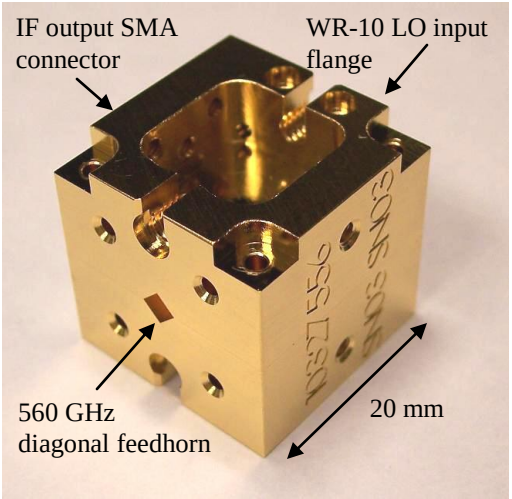

Figure 3: Integrated 560 GHz receiver block, including a 280 GHz tripler MMIC, a 560 GHz sub-harmonic mixer MMIC, an integral diagonal horn at 560 GHz, and an IF circuit and connector. The block is 20x20x20 mm^3 in size.

B. *Measurement results*

Tests have been performed at room temperature in a vacuum chamber using the procedure described in [6]. The integrated 560 GHz receiver front-end is pumped by a W-band Agilent source followed by a W-band power amplifier covering the frequency range 85-103 GHz, with an output power up to 100 mW. A W-band rotary vane attenuator was inserted between the amplifier and the integrated tripler/sub-harmonic mixer to find the best input power.

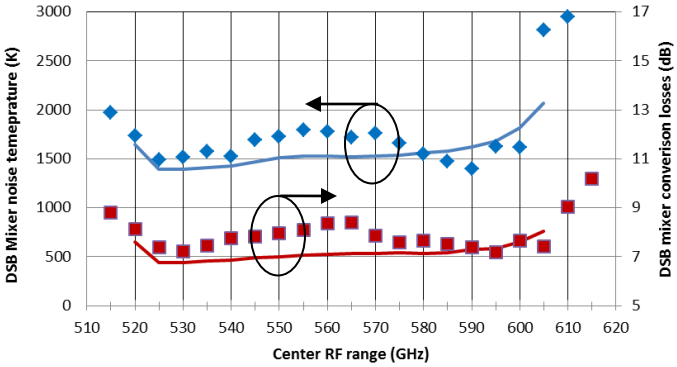

Figure 4: DSB mixer noise temperature and DSB conversion losses measured and simulated of the 560 GHz integrated triper + sub-harmonic mixer. The IF range is between 4 GHz and 6 GHz.

During the test procedure, the reverse bias voltage of the 280 GHz integrated tripler was kept to a fixed value of 8V for simplicity. It appears that it was nearly optimal over the entire frequency range.

As shown in Figure 4, the best performance are obtained at 590 GHz with a DSB mixer noise temperature of approximately 1400 K, and DSB mixer conversion losses of approximately 7 dB. The DSB mixer noise temperature is below 1800 K and conversion losses are below 8.5 dB between 520 GHz and 605 GHz. Figure 4 also shows that the measurement results are in accordance with the simulations.

When cooled at a physical temperature of 150 K, the DSB mixer noise temperature improves by 200 to 300 K in average, and the DSB mixer conversion losses remain stable.

The amount of W-band input LO power required to pump the integrated 560 GHz tripler + sub-harmonic mixer is measured separately using a PM4 Erickson calorimeter, between 20 mW at 600 GHz and 80 mW at 530 GHz.

It is important to notice that previously reported performance of this device in [7] is erroneous as a mistake was made in retrieving the DSB mixer conversion losses. The correct performances are presented in Fig.4 of this paper. It should also be noticed that no correction for feed horn losses and IF mismatch is included. The mixer is measured with an isolator at the IF port to remove all influence from the 1st LNA.

III. 664 GHz RECEIVER DEVELOPMENT AT RPG

A 664 GHz receiver based on MMIC membrane planar Schottky diodes from ACST [8] has been developed. It includes a 332 GHz MMIC Schottky doubler and/or tripler, and a 664 GHz sub-harmonic mixer. Both devices have been designed using a combination of 3D-EM simulations (HFSS from Ansoft) and non-linear circuit simulations (Microwave Office from AWR [9]).

A. Design and fabrication

The 332 GHz doubler and/or tripler are based on a balanced configuration, as introduced by [10] and [4] respectively, using an anti-series and series pair of Schottky diodes respectively. Both Schottky devices exhibit a series resistance of 3 to 5 Ohms, zero voltage capacitance of 16 fF for the doubler and 26 fF for the tripler, an ideality factor of 1.11 and a reverse breakdown voltage of approximately 15V.

The 664 GHz sub-harmonic mixer is based on an anti-parallel configuration, as shown in Fig. 5. Typical DC characteristics of each anode are a series resistance of 14 Ohms, an ideality factor of 1.25, and a zero voltage capacitance below 1.5 fF.

Details concerning the fabrication of the MMIC Schottky devices can be found in a companion paper [11]. The blocks have been machined and assembled at RPG. Figure 6 shows a complete 664 GHz Front-End receiver, including a W-band multiplier-amplifier source that outputs between 50 and 100 mW, a W-band isolator, a 332 GHz tripler and the 664 GHz sub-harmonic mixer.

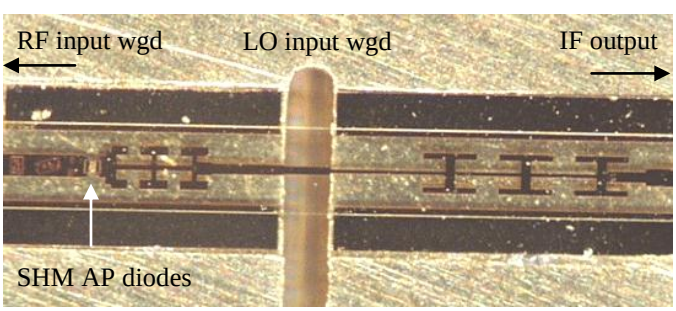

Figure 5: 664 GHz sub-harmonic mixer MMIC fabricated by ACST and mounted inside the lower half of the 664 GHz split-block.

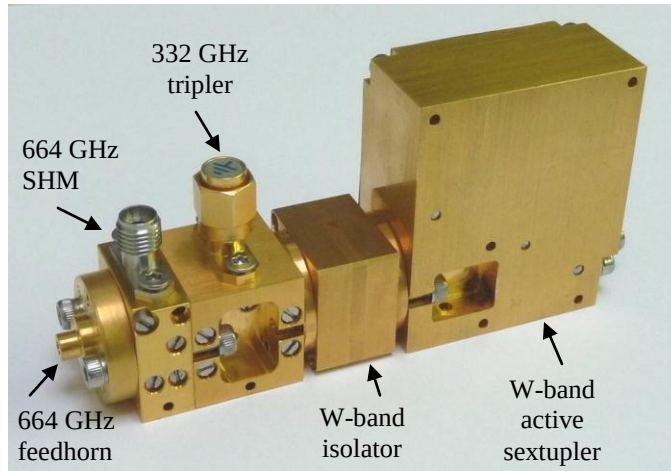

Figure 6: 664 GHz receiver front-end from RPG, including a W-band multiplier-amplifier, a W-band isolator, a 332 GHz tripler, the 664 GHz sub-harmonic mixer and an external 664 GHz corrugated feed-horn.

B. Test results

Test results for the 332 GHz MMIC doubler are shown in Figure 7 for two blocks SN#4 and SN#5. An isolator is inserted between the 166 GHz driver source and the 332 GHz doubler. The maximum output power generated is 10 mW at 330 GHz, with a 3dB bandwidth extending from 326 GHz to 344 GHz for SN#4, and from 324 GHz to 342 GHz for SN#5. With an available input power ranging from 25 to 40 mW, the 332 GHz doubler efficiency ranges from 15 % up to almost 30 % between 326 GHz and 346 GHz. Output powers up to 13-14 mW are achieved if the W-band isolator is removed.

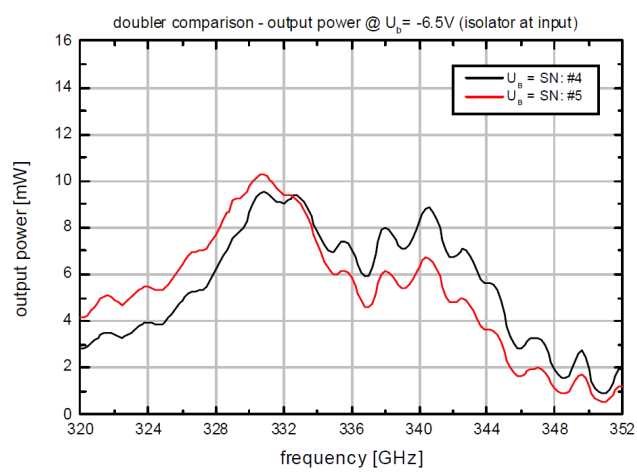

Figure 7: 332 GHz MMIC doubler performance results for 2 blocks.

This 332 GHz multiplier source is used to pump the 664 GHz MMIC sub-harmonic mixer. As shown in Fig. 6, the 664 GHz SHM is directly connected to the 332 GHz doubler, and an external 664 GHz corrugated feed-horn is attached to the mixer. The IF range for this test extends from 1.7 to 6.7 GHz. Two mixer blocks SN#1 and SN#2 were tested.

The results are presented in Fig. 8. The “error bars” are the min/max values within the 1.7-6.7 GHz IF band for each data point.

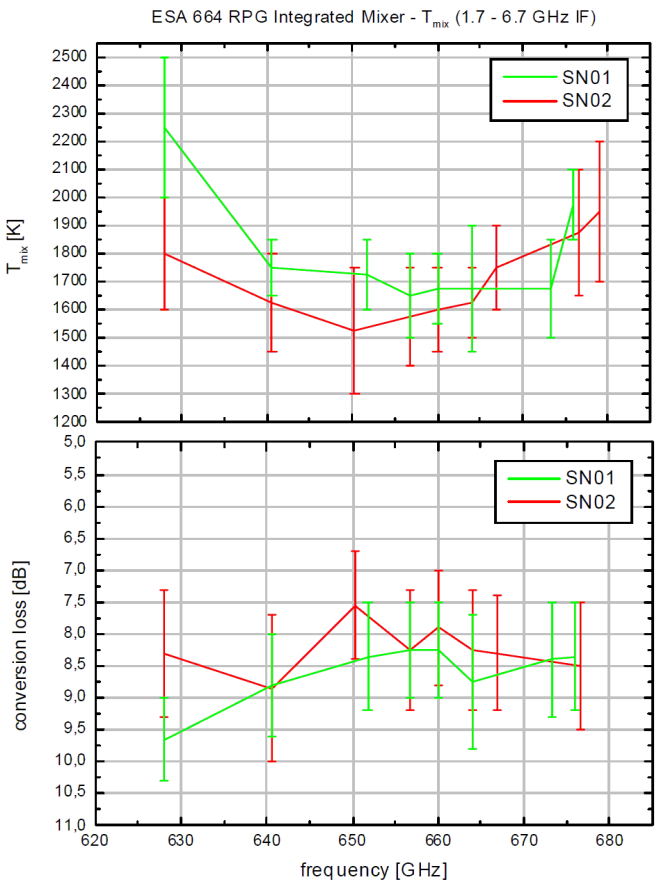

Figure 8: 664 GHz MMIC sub-harmonic mixer performance measured for 2 blocks. The IF range is between 1.7 GHz and 6.7 GHz.

As shown in Fig.8, the DSB mixer noise temperature is between 1550 K and 1800 K in average between respectively 640 and 675 GHz for SN01. The bandwidth is slightly shifted for SN02 between 630 and 670 GHz. The DSB mixer conversion losses are measured between 8.25 dB and 9 dB for SN01, and between 7.5 dB and 9 dB in their respective frequency ranges. The amount of LO power necessary to pump the mixer optimally is around 4.5 mW.

IV. 1.2 THz Receiver Channel

The 1200 GHz channel includes a 200 GHz MMIC membrane doubler, a 600 GHz MMIC tripler similar to the one described in [12], and a novel 1100-1300 GHz MMIC membrane biasable sub-harmonic mixer. The 1200 GHz sub-harmonic mixer architecture is similar to a previous design that gave state-of-the-art results at 874 GHz, as described in [5][6]. It's a balanced design similar to the 560 GHz channel mixer described above, with an additional on-chip capacitor in order to forward bias the diodes in series. This feature should enable to reduce the amount of LO power required to pump the mixer to 1 or 2 mW, as suggested by simulations.

The 1200 GHz sub-harmonic mixer has been designed and fabricated, as shown in Fig.9. The predicted mixer performance is shown in Figure 10. The design methodology and prediction tools are described in [4].

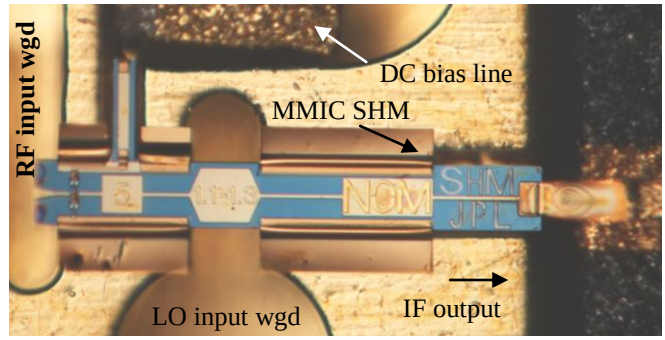

Figure 9: Photo of a MMIC 1200 GHz sub-harmonic mixer based on GaAs membrane Schottky diodes mounted inside the lower half of the split-block.

As shown in Fig. 10, the predicted DSB mixer noise temperature of the mixer is between 4000 and 4500 K at room temperature in the frequency range 1050 to 1280 GHz, corresponding to DSB conversion losses between 12.5 dB and 14 dB approximately.

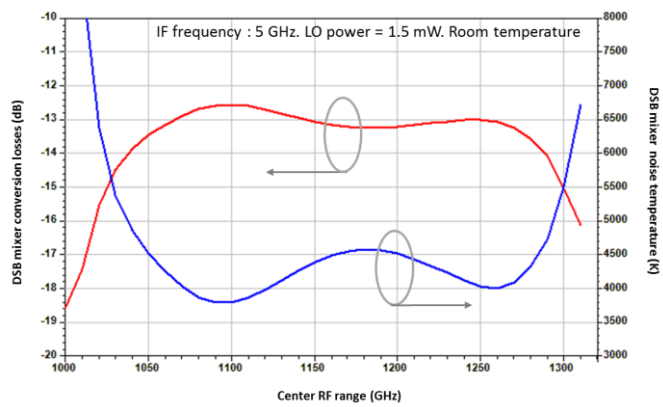

Figure 10: Predicted performance of the MMIC 1200 GHz sub-harmonic mixer at room temperature. IF is fixed to 5 GHz, LO bias is set to 1.5 mW and mixer is DC forward bias to 0.5V per anode.

Test campaign is on-going to measure the performance of the 1200 GHz heterodyne receiver chain.

Conclusion

Several development programs are on-going in Europe and US to push the MMIC Schottky technology well into the sub-millimetre wave region and above 1 THz. Future sub-millimetre wave instruments for the remote sensing of planets' atmospheres such as the Earth, Mars, Jupiter and Saturn will greatly benefit from the recent advances in receiver sensitivity and integration in the 500 to 1200 GHz range, as demonstrated in this paper. The development of MMIC Schottky technology and powerful Local Oscillator sources widely tunable and operating at room temperature are pivotal for planetary remote sensing instruments in the THz range.

ACKNOWLEDGMENT

The authors wish to thank Dr. Peter Siegel for JPL for his constant support and advices. Mr. Peter Bruneau from the machine shop at JPL, and Mr. Benjamin Elsner at RPG are also acknowledged for the superb quality of the micro-machined blocks.

This work has been carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract from the National Aeronautics and Space Administration, and at Radiometer Physics GmbH under contract from the European Space Agency/ESTEC Nr. 21628/NL/GJC.

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