560 GHz, 664 GHz and 1.2 THz Schottky based MMIC sub-harmonic mixers for planetary atmospheric remote sensing and FMCW radar

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***Abstract-* We present here the development of several sub-milllimeter wave heterodyne receivers based on MMIC Schottky. 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 and DSB mixer conversion losses of 7.5 dB at 590 GHz. In addition, a 664 GHz receiver using similar MMIC Schottky devices balanced mixer architecture has been developed. It exhibits good performance with a DSB mixer noise temperature of 2500 K and DSB mixer conversion losses below 10 dB at 670 GHz. Finally, the 1200 GHz channel is under development. It includes 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 is presented.**

I. INTRODUCTION

Sub-millimeter heterodyne receivers using MMIC semi-conductor devices are uniquely suited for long term planetary missions such as EJSM [1], or long term Earth climate monitoring missions such as MetOp SG [2], as they can operate for decades without any active cryogenic cooling. They can give unique insights in the temperature distribution, water vapor content, ice particle sizes, of planets' atmosphere.

Another very interesting application is for FMCW radar for concealed weapons underneath clothing. Indeed, the submillimeter wave range can resolve millimeter scale details at relative long range distances (up to 25-m) thanks to high frequencies and a relative transparency of the atmosphere in certain window channels.

In that context, we present the design, fabrication and test of several sub-millimeter wave receiver front-ends that span in frequency from 520 GHz up to 1300 GHz, using common balanced architecture for all MMIC Schottky components.

First, a 560 GHz receiver has been developed by JPL. It features an integrated 280 GHz MMIC tripler and 560 GHz MMIC sub-harmonic mixer integrated in a single block. In addition, a 664 GHz receiver has been developed. It uses a 332 GHz MMIC tripler and 664 GHz MMIC sub-harmonic mixer (SHM). The receiver architecture and test results are presented. The design, fabrication and tests are presented. The 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, a novel 1200 GHz MMIC sub-harmonic mixer has been designed, and is presented here.

II. 560 GHZ INTEGRATED RECEIVER DEVELOPMENT

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) and linear/non-linear circuit simulations (ADS from Agilent).

A. Design and fabrication

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

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 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 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.

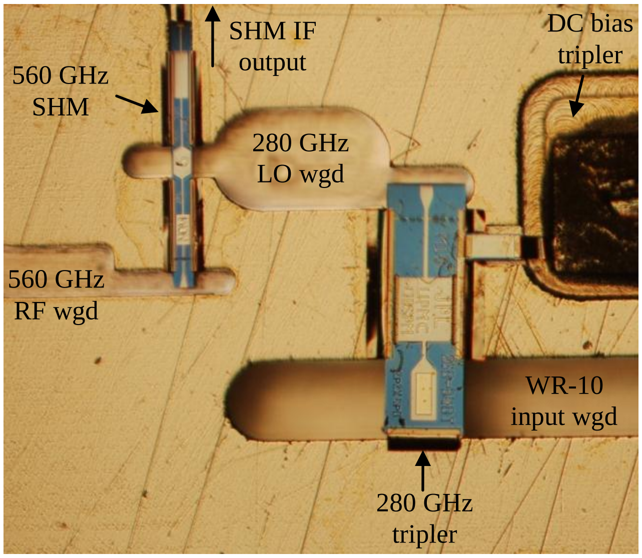

Figure 2: Integrated 560 GHz receiver from JPL, featuring a 280 GHz MMIC tripler and 560 GHz sub-harmonic mixer in a single cavity.

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.

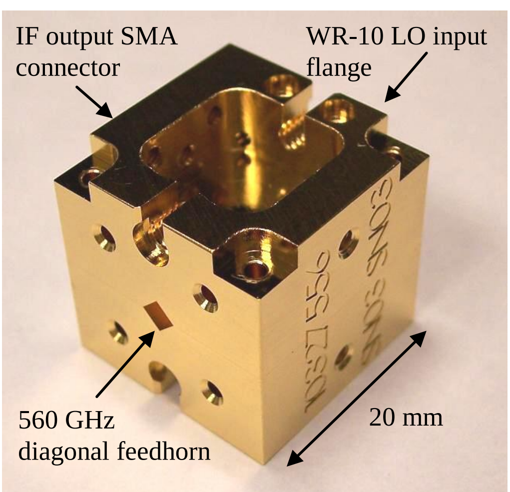

Figure 3: Integrated 560 GHz waveguide block, including a 280 GHz tripler MMIC, a 560 GHz sub-harmonic mixer MMIC, an integral diagonal horn at 560 GHz, and a 2-11 GHz IF matching circuit and connector.

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 HP 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.

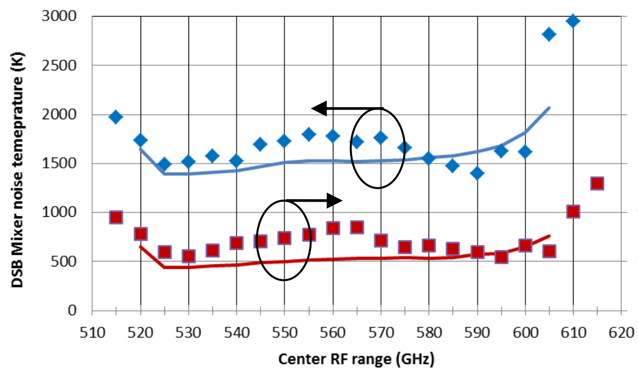

Figure 4: DSB mixer noise temperature and DSB conversion losses measured and simulated of the 560 GHz integrated triper + sub-harmonic mixer. The IF range is between 4 and 6 GHz.

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 obtained are a DSB mixer noise temperature of approximately 1400 K at 590 GHz, corresponding to DSB mixer conversion losses of approximately 7.5 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 30 mW at 590 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 in the mixer performance calculation.

III. 664 GHz RECEIVER DEVELOPMENT

A 664 GHz receiver based on MMIC membrane planar Schottky diodes has been developed. It includes a 332 GHz MMIC Schottky tripler and a 664 GHz sub-harmonic mixer. Both devices have been designed using a combination of 3D-EM simulations (HFSS from Ansys [8]) and non-linear circuit simulations (ADS from Agilent [9]).

A. Design and fabrication

The 332 GHz tripler is a scale version of the one presented in [4], using a pair of anti-series Schottky diodes. It's a 6-anodes balanced design that includes an on-chip capacitor for DC bias.

The 664 GHz sub-harmonic mixer is based on a series balanced configuration derived from [5], as shown in Fig. 5. Typical DC characteristics of each anode are a series resistance between 17 and 21 Ohms, an ideality factor of 1.32 to 1.35, and a zero voltage capacitance below 1.5 fF.

Figure 6 shows a complete 664 GHz receiver Front-End inside the vacuum test chamber, including a WR-08 isolator, a series of cascaded WR-08 amplifier chains, a 332 GHz tripler and the 664 GHz sub-harmonic mixer.

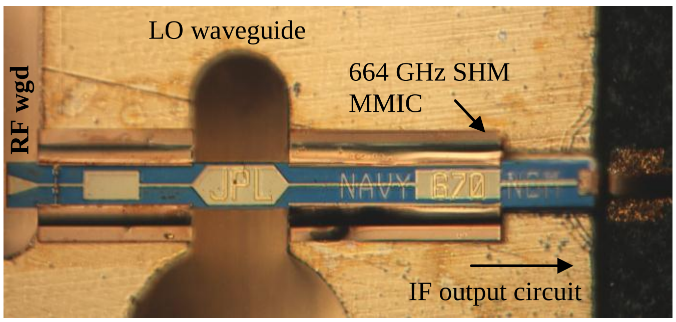

Figure 5: 664 GHz sub-harmonic mixer MMIC mounted inside the lower half of the 664 GHz split-block.

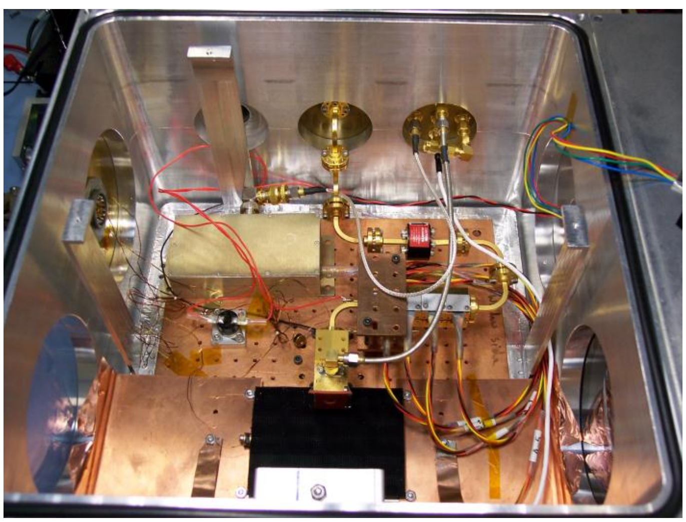

Figure 6: 664 GHz Receiver front-end under test inside the vacuum chamber, including a WR-08 isolator, a series of cascaded WR-08 power amplifiers, a 332 GHz tripler and a 664 GHz sub-harmonic mixer.

B. Test results

Test results for the 332 GHz MMIC tripler are shown in Figure 7. With a fixed input power ranging 75 mW from the cascaded WR-08 power amplifier stage, the typical output power generated ranges between 6 mW and 10 mW in the frequency range 310-350 GHz, corresponding to an efficiency between 7 % and 13 % in this frequency range. Higher output powers could be achieved if the maximum output power of the WR-08 amplifier (100 to 140 mW) was used to pump the 332 GHz tripler. However, in our case, a input power of 75 mW for the 332 GHz tripler is more than enough to pump optimally the 664 GHz sub-harmonic mixer.

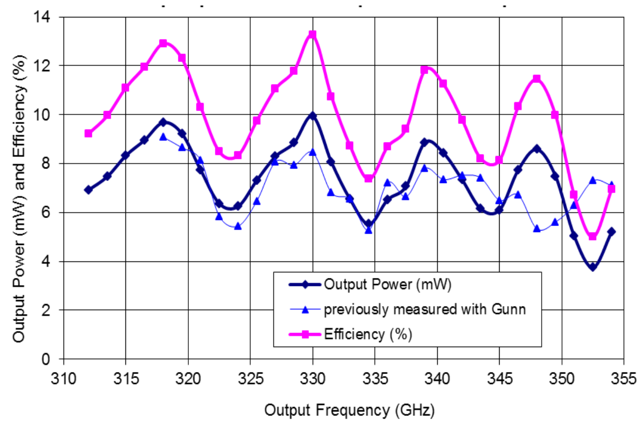

Figure 7: 332 GHz MMIC tripler performance results for a fixed input power of 75 mW between 104 GHz and 118 GHz.

This 332 GHz multiplier source is used to pump the 664 GHz MMIC sub-harmonic mixer. The 664 GHz SHM includes an integral diagonal feedhorn centered and an IF matching circuit from 2-11 GHz. The mixer is tested in the same conditions as previously described [6]. The results are presented in Fig. 8.

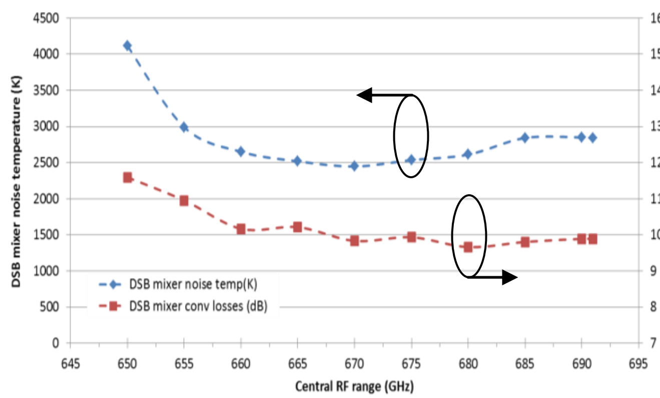

Figure 8: Measured 664 GHz MMIC sub-harmonic mixer performance. The IF range is between 4 GHz and 6 GHz.

As shown in Fig.8, the DSB mixer noise temperature is between 2500 K and 3000 K in average between respectively 655 and 690 GHz. The DSB mixer conversion losses are measured between 9.7 dB and 11 dB in the same frequency range. The amount of LO power necessary to pump the mixer optimally is estimated to be approximately 5 mW. As before, 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.

IV. 1.2 THz Receiver Channel

The 1200 GHz channel includes a 600 GHz LO source based on MMIC membrane 200 GHz doubler and 600 GHz tripler as described in [10][11], and a 1100-1300 GHz MMIC membrane biasable sub-harmonic mixer. The 1200 GHz sub-harmonic mixer architecture is scaled from a previous design at 874 GHz, as described in [5]. 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 enables to reduce the amount of LO power required to pump the mixer to 1 or 2 mW.

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 [6].

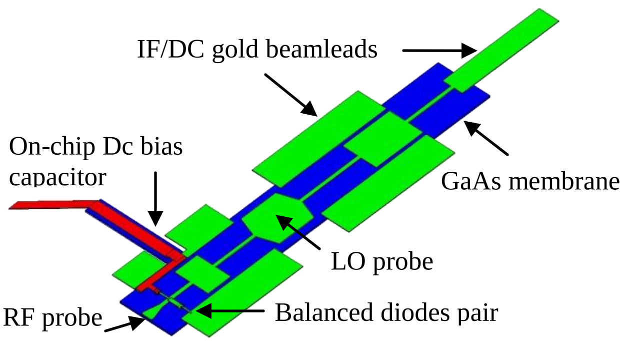

Figure 9: 3D view of the MMIC 1200 GHz sub-harmonic mixer based on MMIC GaAs membrane Schottky diodes, including the on-chip DC bias capacitor (in red).

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.

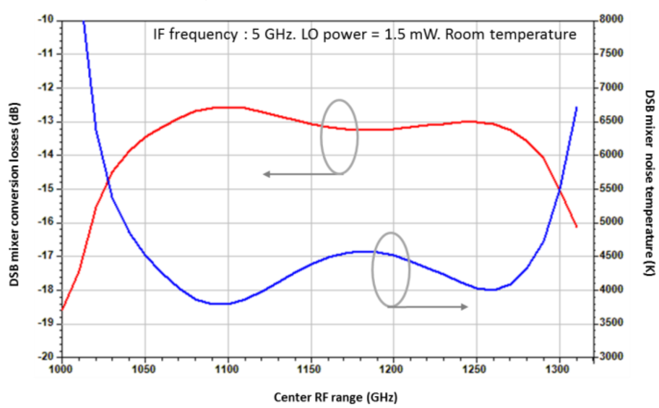

Figure 10: Predicted performance of the MMIC 1200 GHz sub-harmonic mixer at room temperature. IF is fixed to 5 GHz, LO bias is set to 1.5 mW and mixer is DC forward bias to 0.5V per anode.

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

Conclusion

Future sub-millimeter 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 THz receiver development.

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