

# A 330 GHz Frequency Doubler Using European MMIC Schottky Process Based on E-Beam Lithography

*J. Treuttel<sup>1\*</sup>, L. Gatilova<sup>1&2</sup>, F. Yang<sup>1&3</sup>, A. Maestrini<sup>1&4</sup>, Y. Jin<sup>2</sup>, A. Cavanna<sup>2</sup>, T. Vacelet<sup>1</sup>, F. Tamazouz<sup>1</sup>, and J-M. Krieg<sup>1</sup>, C. Goldstein<sup>5</sup>*

<sup>1</sup> Observatory of Paris (LERMA), 61 avenue de l'observatoire, 75014 Paris, France, [jeanne.treuttel@obspm.fr](mailto:jeanne.treuttel@obspm.fr)

<sup>2</sup> Laboratoire de Photonique et Nanostructure (LPN-CNRS), Route de Nozay, 91460, Marcoussis, France.

<sup>3</sup> State Key Lab of Millimeter Waves, Southwest university, 210096 Nanjing China.

<sup>4</sup> Université Pierre et Marie Curie (UPMC), 4 Place Jussieu 75005 Paris, France

<sup>5</sup> Centre National d'Etudes Spatial (CNES), 18 Avenue Edouard Belin, 31400 Toulouse, France

## Abstract

The Submillimetre-Wave Instrument (SWI) is a passive microwave spectrometer included in the large-class mission in ESA's Cosmic Vision Jupiter ICy moons Explorer (JUICE). It will spend at least three years making detailed observations of the molecular spectral signature of the atmospheres of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa. The Submillimeter Wave instrument consists in a 600 GHz radiometer that involves compact, non-cryogenic Schottky diodes based solid-state devices for the mixer and last stage local oscillator frequency multipliers. LERMA-LPN is in charge of the SWI local oscillator 280 GHz last stage frequency doubler. In this article we report on recent progress of LERMA-LPN Schottky diode process for the 310-360 GHz prototype circuit that is proposed during the first phase of the program. It is fully based on e-beam lithography for the highest precision of small features, like the anodes and the air-bridges. This multiplier features 4 anodes in a balanced configuration monolithically integrated on a 5 $\mu$ m-thick GaAs membrane circuit connected to a split waveguide-block by metallic beam-leads. The circuit has been mounted in a split block with techniques that will facilitate space qualification. A conversion efficiency of about 15-22% has been measured in the 310-360 GHz band, in very good agreement with simulations. A lifetime test over more than 1600 hours of continuous RF operations with 45 mW of input power has been successfully recorded at LERMA. The design, fabrication process and measurement of the LERMA-LPN 310-360 GHz frequency doubler will be presented at the conference.

## 1. Introduction

Jupiter ICy moons Explorer (JUICE) is the first large-class mission in ESA's Cosmic Vision 2015-2025 program, that is planned for launch in 2022 and arrival at Jupiter in 2030. The Submillimeter Wave Instrument (SWI) will study the Galilean satellites, the chemistry, meteorology and structure of Jupiter's middle atmosphere and atmospheric and magnetospheric coupling processes. SWI will provide unique inputs for the exploration of the habitable zones of Ganymede, Europa and Callisto in characterizing Ganymede as a planetary object and possible habitat and exploring recently active zones of Europa's young icy crust. Furthermore it will explore the Jupiter system as an archetype for gas giants in characterizing the Jovian atmosphere and its satellite and ring systems [1]. In order to fulfill these science goals the instrument will make radiance measurements of atmospheric emission lines at very high spectral resolution to determine atmospheric composition, temperature, and dynamics. The SWI instrument consists in a spectrometer/radiometer operating in its baseline configuration in two identical heterodyne channels at submillimeter wavelength around 600 GHz. It is a development goal to later replace one of these channels by a shorter wavelength channel around 1.2 THz. The instrument will operate in space environment that presents a major problem to all spacecraft, and more so for the Jupiter Icy Moons Explorer, which amongst others will have to endure the extreme environment of the planet Jupiter. In order to keep the spectral resolution in the specific Jovian radiation environment, the SWI will be based on compact, non-cryogenic Schottky diodes solid-state technology for the mixer and the last stages local oscillator frequency multipliers. In this program, LERMA-LPN is in charge of the local oscillator last stage frequency doubler which nominal frequency is 280 GHz. A 310-360 GHz prototype circuit has been developed during the first phase of the program and is presented in this article. Firstly we will present the design

methodology, then we will describe the fabrication and preliminary lifetime measurements performed in laboratory conditions.

## 2. 330 GHz MMIC Circuit design

The circuit design of a 310-360 GHz fixed-tuned MMIC doubler is based on the balanced topology presented in [2]. The frequency was chosen according to the available laboratory test equipment to be as close as possible to the nominal 280 GHz band. The 320 GHz doubler features an anti-series set of four planar Schottky diodes integrated within the passive suspended microstrip circuit onto a 5  $\mu\text{m}$  thick GaAs membrane that is connected to a split waveguide-block by metallic beam-leads. The circuit geometry prevents the input fundamental signal from leaking into the output and also prevents the output second harmonic signal from leaking into the input waveguide. Moreover, the reduced height input waveguide cut off the input signal TM<sub>11</sub> mode for a more efficient coupling to the diodes. A stepped impedance filter section at the opposite end of the circuit is used as a DC bias voltage path that block any leakage of the second harmonic through this port. Therefore on-chip capacitor is not necessary for DC-RF decoupling.

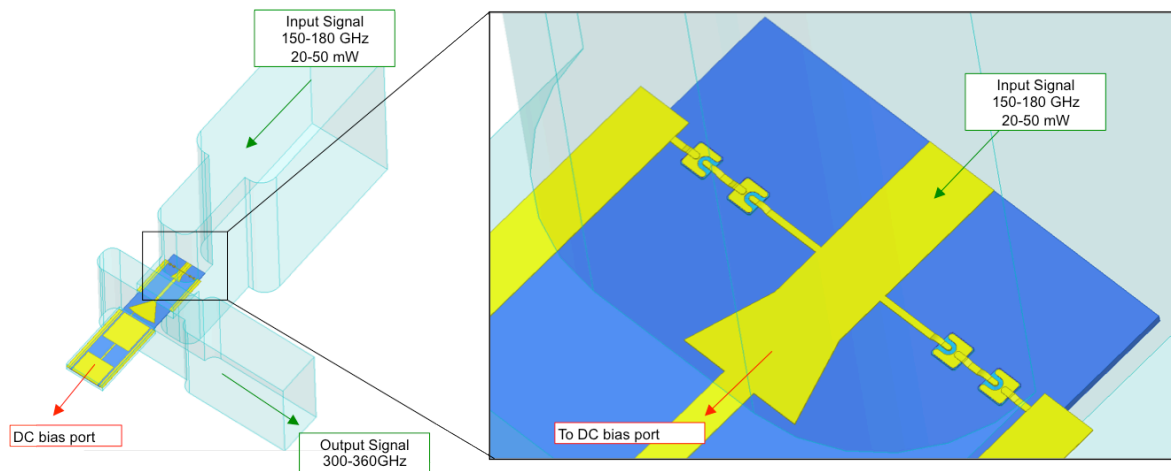


Fig. 1. 310-360 GHz frequency doubler MMIC circuit design simulated in its 3D EM environment.

The methodology used for the design uses a combination of non-linear circuit simulations (Agilent ADS) and 3D electro-magnetic simulations (Ansoft HFSS) that is based on the methodology presented in [3]. To start with, a standard diode model customized with in-house parameters was implemented together with its close 3D passive environment (diode cell), plus ideal input and output matching networks. During this simulation, the anode zero junction capacitance and the diode cell geometry, including anodes positions, input channel width and input stub length, were optimized using the harmonic balance and optimization routines of ADS in order to reach optimum power efficiency. Then, each transition in the circuit including step impedances, coupling probes and waveguide transitions were simulated within the 3-D electromagnetic environment with appropriate boundaries, waveports assignment and de-embedding planes. The simulation outcomes (2-D S-parameter matrices and their attenuations, impedances and permittivity values at central guided frequencies) were used in a global non-linear optimization. During this second optimization step, ideal  $\lambda/4$  initial lengths were defined in the step-impedance filter and matching network in order to converge to optimum lengths of the circuit transmission lines. Several iterations were necessary to define the appropriate dimensions of the position of the input back-short, the diodes geometry, the input stub near the diodes and the output probe in order to reach a wide impedance matching over the input frequency band. Finally, the values found during the previous steps were feed back in HFSS to build the full doubler circuit structure as shown in Fig. 1, and the circuit was finally simulated with the harmonic balance routine to check the doubler coupling efficiency, global efficiency and output power. The electrical parameters of the LERMA-LPN Schottky diode model considered in the simulations are a series resistance  $R_s = 7\Omega$ , an intrinsic zero voltage junction capacitance of  $C_{jo} = 17 \text{ fF}$ , a saturation current  $I_{sat} = 150 \text{ fA}$ , an ideality factor  $= 1.3$  and a built-in potential  $V_{bi} = 0.85 \text{ V}$ . This design was optimized for 30 mW of input power and  $-3.5\text{V}$  bias voltage.

## 3. 330 GHz doubler fabrication

MMIC technology applied to integrated Schottky structures is the key issue to lead to reproducible circuit performances that will fulfill JUICE environmental conditions. As described in the previous section the fabricated

LERMA-LPN 330 GHz MMIC doubler circuit features four anodes integrated onto a 5  $\mu\text{m}$ -thick GaAs membrane. The membrane epitaxial levels were grown in-house by MBE technique at LPN. The beamleads are thin gold layers that allow suspending the circuit in the waveguide. They have been done using a front-side process.

The input and output waveguides, the microstrip channel and the DC bias connector sockets are milled into two split-waveguide blocks made out of brass. Two different blocks have been fabricated by SAP-micromechanics and gold plated by Gallion SA. The MMIC circuits have been mounted into their respective blocs with a special care to fit spatial requirements as illustrated in Fig.2. The beamleads are thermo-compressed onto the block, therefore it is expected to have very limited mechanical stress on the device due to differential dilatation. The DC connection is performed with bondings to the glass bead of the K-connector. During the mounting stage, no conductive glue is used.

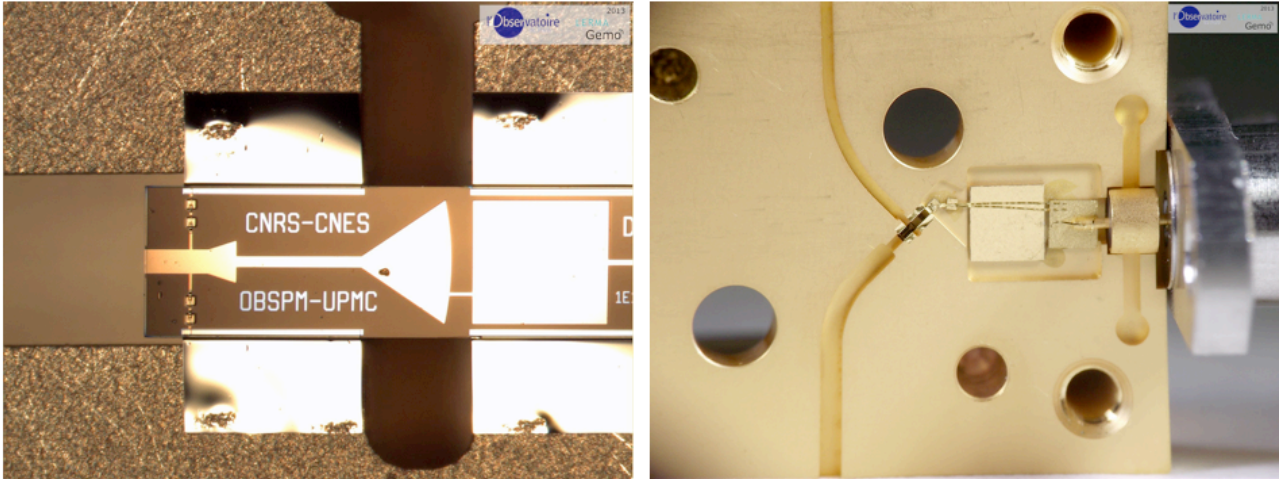


Fig. 2: Mounting of the LERMA-LPN 330 GHz MMIC doubler into mechanical split-blocks.

#### 4. 330 GHz doubler measurement

Before hand, I-V on-wafer measurement before passivation have been performed, giving excellent diode I-V curve and  $\Delta V$ , with the  $\Delta V$  defined as  $\Delta V = V(I=100 \mu\text{A}) - V(I=10 \mu\text{A})$ . Typically, the  $\Delta V$  per diode is 70 mV and the breakdown voltage per diode is -12/-13V. A test bench for statistical characterization of the diodes is currently being developed and applied in order to meet ESA's space qualification of the LERMA-LPN Schottky process. It consists in reaching a good and stringent statistics of the diode parameters after successive heatings of the diodes.

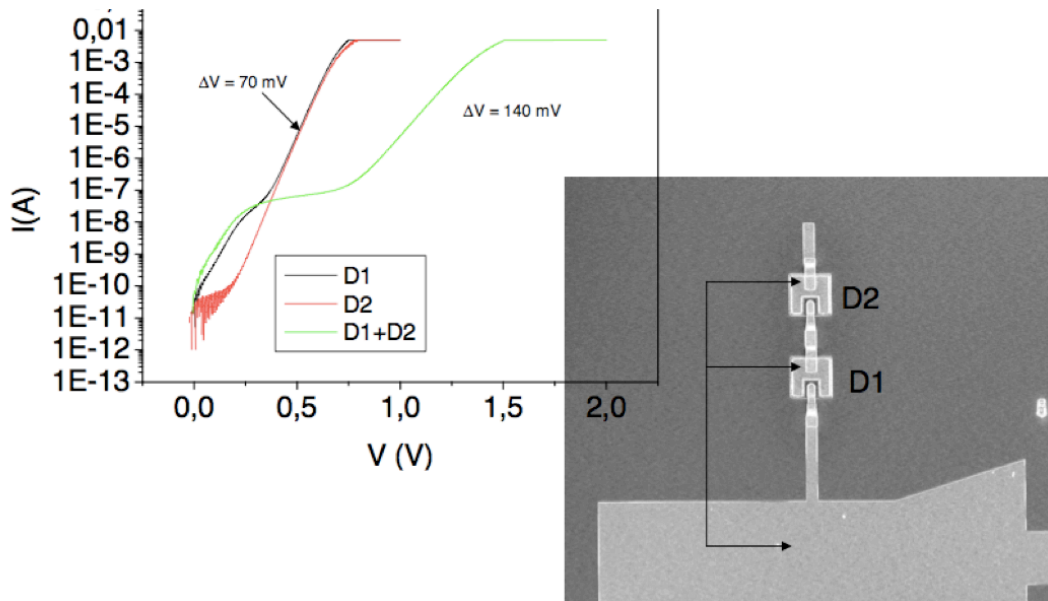


Fig.3 : LERMA-LPN 330 GHz MMIC doubler : On-wafer measurement before passivation. Diode I-V curve and  $\Delta V$ .

An other test bench consists in measuring the RF output power of the 330 GHz MMIC LERMA-LPN doublers. As illustrated in Fig. 4, the power measurement gives 15-22% of power efficiency across the 310-350 GHz band, with 7 mW of output power peak at 334 GHz. The measurement of the two blocs has been obtained in one day interval giving very similar results and a good fit to the design simulation results. The bandwidth efficiency will be explored below and above 310 and 350 GHz when the input power source will allow it. A lifetime test over more than 1600 hours of continuous RF operations with 45 mW of input power has been successfully recorded at LERMA.

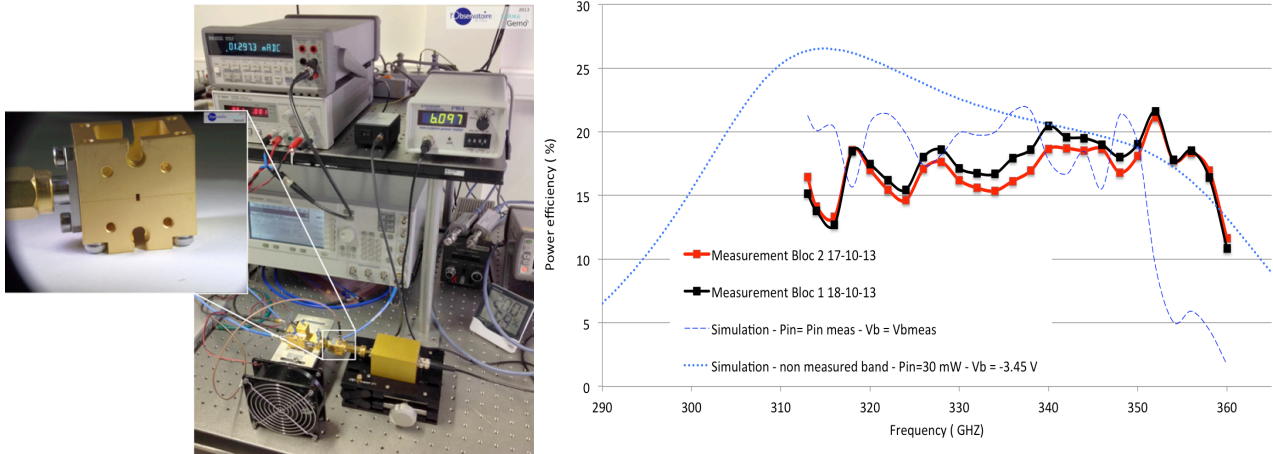


Fig.4 : Power efficiency measurement of two different blocks of the LERMA-LPN 330 GHz MMIC doubler without correction. Comparison with simulation.

## 5. Conclusion

The development of Schottky devices for THz applications is jointly carried out by Observatory of Paris - LERMA and CNRS - LPN which is a leading French national nanofabrication center with a complete setup for nano and micro devices fabrication and characterization. The nano-schottky diodes on GaAs membranes are fabricated with a process entirely based on electron-beam lithography and feature sub-micron anodes, short and narrow airbridges and front-side process beam-leads. A fully integrated 330 GHz doubler was fabricated and mounted in a split-block in the context of SWI-JUICE ESA program. The circuit was successfully measured up to 1600 hours at RF frequency and gives about 15-22%, power efficiency and 7 mW of maximum output power with 45 mW of input power. This result is a first and significant step for the MMIC LERMA-LPN technology at Terahertz frequencies.

## 6. Acknowledgments

The presented 310-360 GHz MMIC doubler was developed under CNES Schottky R&T programs R-S11-SU002-54 and R-S12-OT-002-069.

## 7. References

1. JUICE – Jupiter Icy Moons Explorer SWI – Submillimetre Wave Instrument (SWI), *Science Concept Document*, JUI-MPS-SWI-PL-002, 13/05/2013.
2. N.R. Erickson “Wideband High Efficiency Planar Diode Doublers”, *Ninth Int' Conference on Space THz Technology*, pp.473-480, Pasadena, CA, 1998.
3. Maestrini, A., B. Thomas, H. Wang, C. Jung, J. Treuttel, Y. Jin, G. Chattopadhyay, I. Mehdi, and G. Beaudin, “Schottky diode based terahertz frequency multipliers and mixers”, invited paper, *Comptes Rendus de l'Académie des Sciences, Physique*, Vol. 11, n°7-8, August-October 2010.