Present and future R&T development in CNES for Microwave radiometer

C.Goldstein[1], M.Trier[2], A.Maestrini[3], J.-C Orlhac[2]

1: CNES, Centre National d'Etudes Spatiales, 18 av. E. Belin, 31401 Toulouse CEDEX 9, France
Tel. (+33) (0)5 61 28 13 32 - E-mail : christophe.goldstein@cnes.fr
2: EADS Astrium, 31 av. des Cosmonautes 31402 Toulouse CEDEX 4, France
3: Observatoire de Paris-LERMA, 61 av de l'Observatoire 75014 Paris, France

Abstract — **The paper describes CNES R&T activities in terms of radiofrequency radiometric equipment. K and Ka band direct detection receivers developed with EADS Astrium use the UMS PH 25 foundry technology. Two applications on spatial microwave radiometers are shown. In the continuity of this action, activities are led on "LNA in front" receivers at 150 and 183 GHz. In parallel, activities on Schottky diode based receiver are led with Observatoire de Paris on MMIC integrated design.**

I. INTRODUCTION

Since 1998, The French space agency carries out R&T actions to prepare the next generation of microwave radiometers. The aim of these actions is not only to improve radiometric performances but to optimise also volume, mass and consumption, parameters which are critical in the frame of a space accommodation. For this, a new generation of direct detection receivers is under development, taking into account the latest technology advance in terms of MMIC. Nevertheless, these technologies do not still permit short or mean term application for receivers above 200 GHZ. For these frequencies Schottky diode based MMIC are developed.

II. K AND KA BANDS DIRECT DETECTION RADIOMETER RECEIVERS

Introduction

Earth Observation by Remote Sensing extensively use microwave in the range of 18 to 40 GHz. Thanks to the emergence of very low noise active technologies based on low gate length High Electron Mobility Transistors (HEMT), MMIC Low Noise Amplifiers (LNA) are now preferred to Schottky diode mixers, for noise figure performance in front end.

The architecture can be simplified as well if the detection can be achieved at the input frequency, avoiding the need for a frequency translation and the associated Local Oscillator source.

The reduction in volume (no bulky waveguide equipment), mass and power consumption are very effective features for the satellite platform accommodation of complex multi frequency microwave radiometer.

This rationale has led the CNES to select EADS Astrium France to study the feasibility of 10 up to 40 GHz Direct Detection Radiometer Receivers suitable for space application with launch planned in 2007.

Receiver Design Drivers and Architecture

The radiometer quality is essentially measured by the radiometric sensitivity (minimum measured effective brightness temperature T_{IN}) and radiometric absolute accuracy. When the mission parameters such as channel bandwidth B and integration time τ are selected, the receiver noise temperature T_{REC} directly impacts the radiometric sensitivity Noise Equivalent ΔT (NEΔT), and then should be minimized.

$$NE\Delta T = (T_{REC} + T_{IN})\sqrt{\frac{1}{B\tau} + \left[\frac{\Delta G}{G}\right]^2} \quad (1)$$

where $(\Delta G/G)^2$ is the short term gain stability (STGS)

At the receiver level, the radiometric absolute accuracy is driven by the square law detection "linearity" (mV dc/mW RF) and the end-to-end gain receiver frequency response including in-band and out-of-band performances and also noise frequency response.

Based on these criteria the architecture selection is a question of compromising the receiver noise figure, the linearity and the frequency response.

LNA ahead is a natural choice providing no strong spurious signal could interfere, and then the other amplifiers and filters stages are distributed such that the linearity and out-of-band performances are reached.

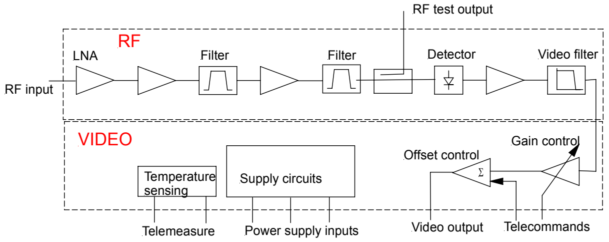

Figure 1. Direct Detection Radiometer Receiver block diagram

In the scope of the initial Research and Technology study, four frequencies were considered: 10.6, 18.7, 23.8 and 36.5 GHz. Apart from the MMIC amplifiers, the other critical functions are the channel filter and the detector. For the later, commercially available tunnel diode detector meets the requirement for frequency, detection sensitivity and temperature stability. The filter feasibility in planar technology is conditioned by the centre frequency and the relative bandwidth requirements. For the frequency plan in next table,

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a special effort needs to be undertaken in order to achieve high quality factor resonators so that percent magnitude relative bandwidth can be achieved without excessive in-band roll off.

Center Frequency (GHz)	10.65	18.7	23.8	36.5
Bandwidth (MHz)	100	200	400	1000
Relative Bandwidth	0.9%	1.1 %	1.7 %	2.7 %

Table 1. Main frequency requirements

After the first step study, the 10.6 GHz was given up as a singular case with respect to filtering constraints as well as bringing doubtful benefit in terms of mission definition.

MMIC Amplifiers

In a framework of a soon coming development only a space qualified technology could be selected. The MMIC amplifiers have been designed using the UMS PH25 foundry technology. This technology is a 0.25 um gate length HEMT on GaAs evaluated by ESA for space application. The design has aimed to optimize the performances in the different frequency bands for noise figure as well as gain.

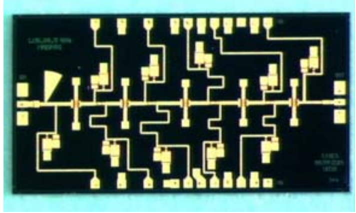


Figure 2. MMIC photography (chip 2x3.5 mm²)

The design process demanded two runs, the second one was necessary to center the circuits in frequency.
For each frequency, two different gain chips have been designed in order to set up the receiver chain overall gain.

Center Frequency (GHz)	18.7	23.8	36.5
Noise Figure (dB)	1.5 (1.7)	1.7 (2)	2.5 (2.8)
Gain (dB)	23 (30)	22 (29)	24 (30)

Table 2. MMIC amplifiers on wafer measured performances (2 chip types per frequency)

The MMIC amplifiers are hermetically sealed in order to meet the lifetime requirement for storage as well as operation.

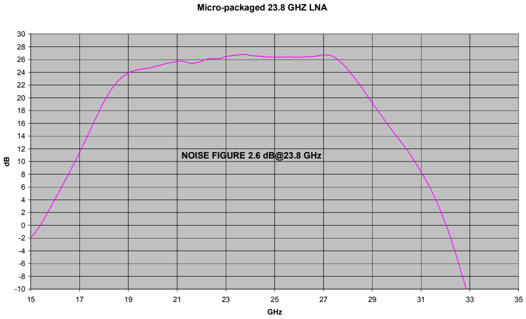
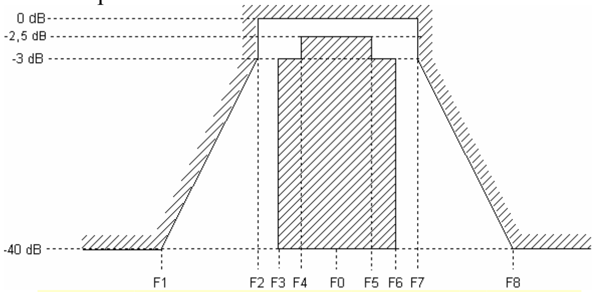


Figure 3. Packaged 23.8 GHz LNA measurement

Channel Filters

The radiometric frequency channel is basically defined by the bandpass channel filter. The receiver in-band gain flatness response will depend mainly on the amplifiers gain and mismatch performances.



F0	**F1**	**F2**	**F3**	**F4**
18.7 GHz	F0-250 MHz	F0-100 MHz	F0-90 MHz	F0-68 MHz
23.8 GHz	F0-500 MHz	F0-200 MHz	F0-180 MHz	F0-135 MHz
36.5 GHz	F0-1250 MHz	F0-500 MHz	F0-450 MHz	F0-338 MHz

F0	**F5**	**F6**	**F7**	**F8**
18.7 GHz	F0+68 MHz	F0+90 MHz	F0+100 MHz	F0+250 MHz
23.8 GHz	F0+135 MHz	F0+180 MHz	F0+200 MHz	F0+500 MHz
36.5 GHz	F0+338 MHz	F0+ 450 MHz	F0+500 MHz	F0+1250 MHz

Figure 3. radiometric channel frequency template specification

The out-of-band specification rejection allows for a classical 5-poles Chebishev topology. The very narrow band leads to a requirement of high quality factor (Q) planar resonator. Conventional microstrip lines on alumina cannot fulfill the needs. Hence suspended microstrip lines photo-etched on low loss quartz dielectric have been selected which ultimately provides a Q factor up to 700 at 36.5 GHz.
The need for a planar industrial design (providing integration capability) prevents from mechanical adjustability, hence leading to the need for several filter variants to meet the frequency accuracy.

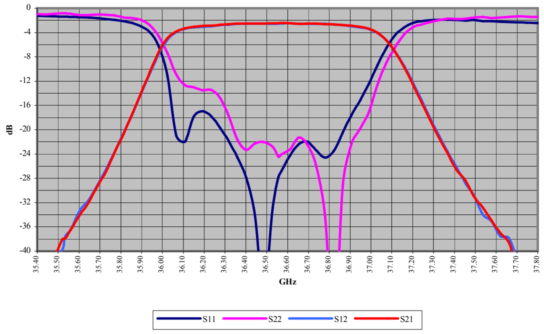


Figure 4. 36.5 GHz demonstration filter measurement

23.8 GHz Elegant Breadboard

The integration of all the RF and Video functions in a single mechanical housing meeting the environmental requirement including Mechanical, Thermal, Electro Magnetic Compatibility as well as standard Electrical interface has been realized during the demonstration phase of the MADRAS radiometer (Megha-Tropiques ISRO-CNES mission). Apart from breadboards manufactured and tested at 18.7 and 36.5 GHz, an Elegant Breadboard (EBB) has been developed and successfully tested under all environmental conditions. This EBB has been manufactured using commercially available parts but with qualified materials and processes.

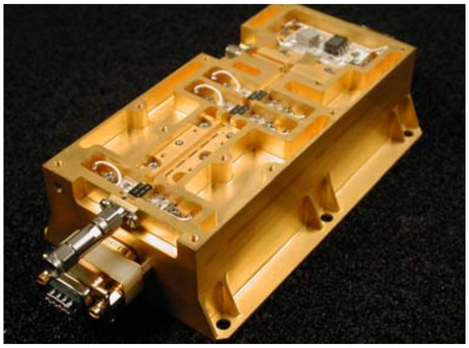


Figure 5. 23.8 GHz Elegant Breadboard

The main performances measurements are provided in Table 3. The Figure 6 shows the Receiver frequency responses, RF chain measured with a network analyser and End-to-End response measured from RF input power to Video output voltage.

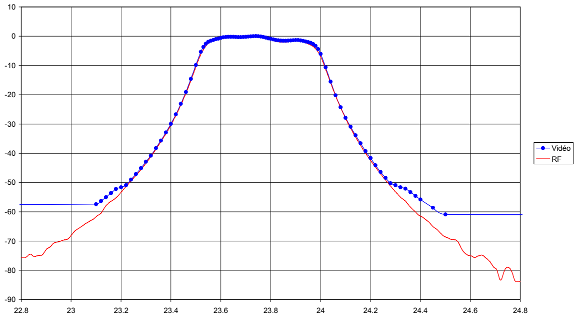


Figure 6. RF chain and End-to-End frequency responses

Performance	*Unit*	*Measurement*
3dB bandwidth	MHz	414 around 23.78 GHz
Noise Figure	dB	2.7 max within +5 +55°C
Transfer gain	mV/K	32
Gain flatness	dB ptp	2.2
NEΔT	K	0.35 within +5 +55°C
STGS (ΔG/G)²		20E-9 over 100ms to 3s time scale
Linearity		5E-4
Power consumption	W	2.76
Mass	g	800

Table 3. 23.8 GHz EBB measured main performances

III. APPLICATIONS

MARFEQ

MEGHA-TROPIQUES is an Indo-French mission designed to study convective systems, focusing on the analysis of water cycle with water vapour distribution and transport, convective systems life cycle and energy exchanges in the tropical belt.

The mission will fly a satellite carrying 3 scientific passive instruments which are :

- MADRAS Instrument : A multi – channels self calibrating microwave imager mainly aimed at studying precipitation and cloud properties.
- SAPHIR Instrument : A microwave instrument used to retrieve water vapour vertical profiles.
- SCARAB Instrument : An optical radiometer devoted to the measurement of outgoing radiative fluxes at the top of the atmosphere.

MARFEQ (MAdras RF EQuipment) is theRF sensor developed by CNES and EADS Astrium. It is a total power radiometer composed of two sub equipments:

- MARFEQ A includes the RF receivers and the main antenna.
- MARFEQ B is the calibration unit including an on board calibration target at ambient temperature and an auxiliary antenna devoted to cold sky measurement.

MARFEQ is a five frequencies radiometer from 18 to 157 GHz K and Ka band receivers are used for the three lower frequencies: 18, 24 and 36 GHz. The sensitivity required for these channels is 0.5 K for an integration time of 16 ms.

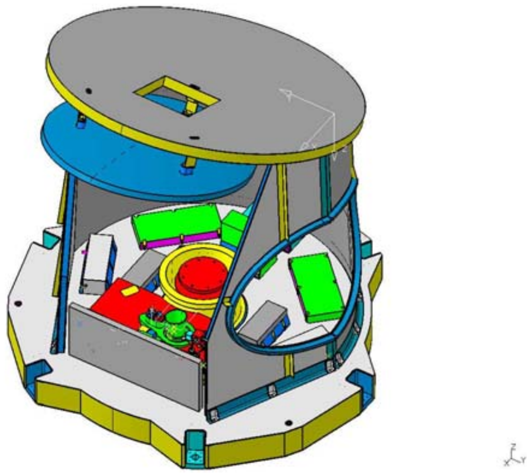


Figure 7: MARFEQ A equipment

AltiKa

In partnership with scientific laboratories and industry, and for several years, CNES has studied the feasibility of a high-resolution ocean topography mission based upon a new class of wide-band Ka-band altimeter in preparation of the post-ENVISAT-RA2 mission and in order to complement the OSTM/Jason-2 mission. The altimeter is delivered by Alcatel Alenia Space. A dual frequency microwave radiometer (23.8 and 37 GHz) using K and Ka band receivers is embedded in the altimeter. This radiometer is required for tropospheric correction. The sensitivity required are 0.3 K (K band) and 0.4 K (Ka band) for an integration time of 20 ms. The radiometer receivers are delivered by EADS Astrium.

The radiometer must be switched-off during radar altimeter emission. In the nominal mode, radiometer receivers measure antenna temperatures. In the internal calibration mode, receivers are either connected to a sky horn pointing to deep space (cold reference) or to a load at ambient temperature (hot reference). This internal calibration can be performed every few seconds. Measured temperatures are averaged over 200 ms. The radiometer calibration unit performs altimeter bandwidth filtering and commutation to calibration sources. This calibration unit is developed by Alcatel Alenia Space.

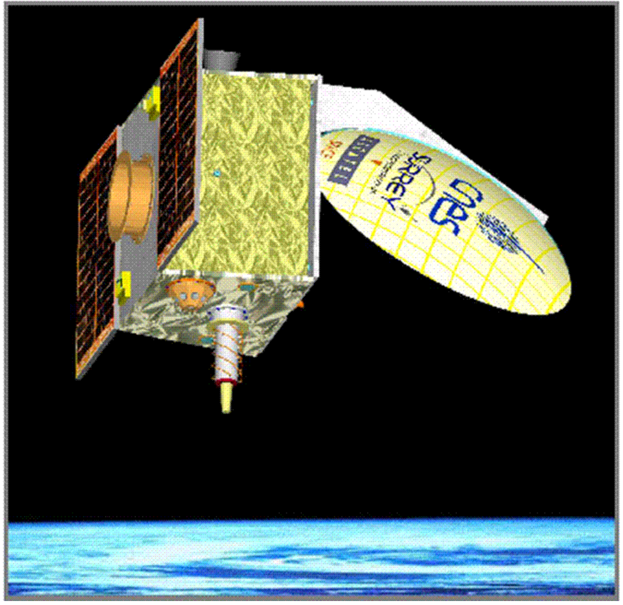


Figure 8: AltiKa in microsat configuration

IV. IMAGING RADIOMETER AT MILLIMETER & SUB MILLIMETER WAVELENGTH.

Introduction

In the continuity of the previous activities in K & Ka frequency bands, and in complement to a technology R&D on MMIC LNA, a receiver system study at 150 GHz & 183 GHz has been performed to demonstrate the feasibility of a receiver using LNA ahead. MMIC based LNA in front end are preferred to Schottky diode mixers for lower mass, volume and consumption with equivalent noise figure performances. 150 GHz receiver use direct detection architecture while 183 GHz is heterodyne receiver.

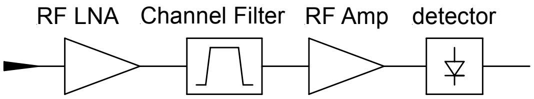


Figure 9 : 150 GHz direct detection receiver

At 150 GHz channel, direct detection receiver is well matched because of uniform distribution of the power (continuum) and sufficient large bandwidth. Receiver performances objectives are : NF : 5.5 dB , BW : 2 GHz.

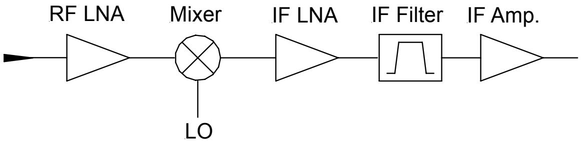


Figure 10 : 183 GHz direct detection receiver

The measurement of the 183 GHz water vapour atmospheric line profile requires simultaneous measurements at many sub channels. The very low relative bandwidth of sub channels prevents to realize filter at RF frequency. IF transposition reduces the relative bandwidth of filters. Moreover, each sub channel requires a detector which is easier and less expensive to realize at IF frequencies. Receiver performances objectives are : NF : 6 dB , BW : 12 GHz

System analysis

The radiometer quality is essentially measured by the radiometric sensitivity (NEΔT), which should be minimized.

$$NE\Delta T = (T_{REC} + T_{IN})\sqrt{\frac{1}{B\tau} + \left[\frac{\Delta G}{G}\right]^2}$$

where $(\Delta G/G)^2$ is the short term gain stability (STGS)

The objective of the system analysis is to determine the best architecture for the receiver (mainly at 183 GHz where several possibilities exist) and to derive modules performances requirements.

150 GHz receiver analysis

The Spectrasys tool of Genesys Eagleware software has been used for all the simulations. System model of active elements including non linear effects and noise are efficient for such analysis. The possibility to use S parameters matrix from circuit simulations or measurements data allow to obtain more realistic results (i.e. mismatch and noise mismatch).

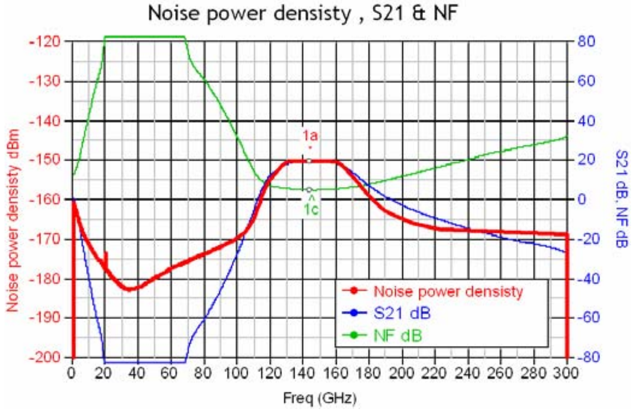


Figure 11 : Noise power density at LNA output

The above figure shows the noise power density at the LNA output. Effect of amplifier noise (in & out of band) is visible on power density plot. In addition with total power along the chain, we can optimize the filter position to minimize non linearity (compression effect) and maximize S/N ratio.

183 GHz receiver analysis

183 GHz heterodyne receiver can use DSB or SSB mixer architecture. DSB and SSB mixing architectures are compared

with respect to upper / lower side band balance and image band rejection.

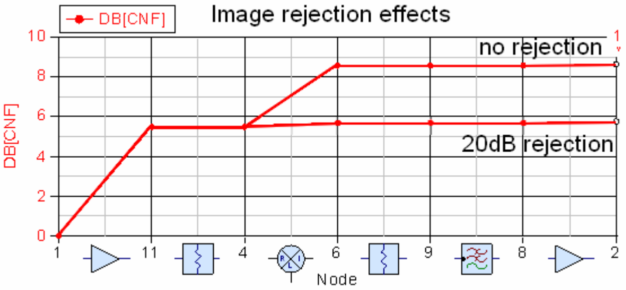


Figure 12 : Cumulated NF versus image rejection level

Degradation of 3dB of the NF due to the not rejected image band noise.

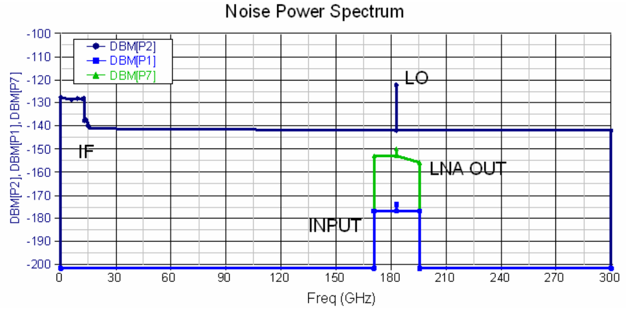


Figure 13 : effect of gain unbalance between side band

In DSB architecture, the LNA gain (or NF) differences between upper and lower side band impact the receiver NF. Real LNA S parameter matrix can be used in receiver model to simulate the impact on performances. In this case, noise, gain and mismatch versus frequency are taken into account to process the performances specification of each module.

V. Schottky diode based heterodyne receivers at 183 GHz and Above

Introduction

The water vapour line at 183 GHz is of prime importance for the study of atmosphere. For the next generation of the SAPHIR instrument, CNES and Observatoire de Paris have a clear interest in being able to build heterodyne receivers targeting this particular frequency. The combination of a mixer and a multiplier in a single chip is an interesting field of research. This paper will give some preliminary ideas on architecture and performances of combined mixers/multipliers.

UMS diodes

The diode has two pads to connect the chip to a micro-strip matching circuit. A finger connects the anode to one of the pads; it is a taper from the anode pad to the anode. The shape of the taper can be customised. A fully parameterised 3D model of the diode was created with Ansoft HFSS. This model was then cloned and included in a 3 D model of the entire mixer or multiplier circuit. Electrical parameters are implanted in the circuit simulator via the standard diode model of Advanced Design System suite (ADS) from Agilent. The intrinsic capacitance and the series resistance are estimated for each diode geometry studied in order to define the optimised mixer diode for the application.

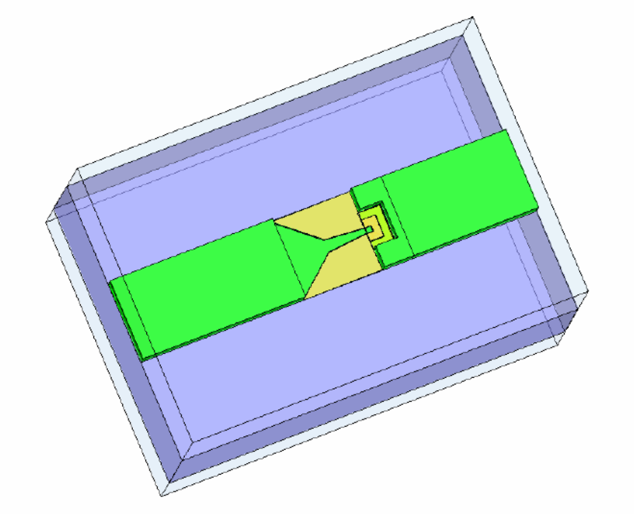


Figure 14: View of a single anode Schottky diode of UMS as modelled with HFS

Before beginning the design of a complete mixer, it is necessary to study the practical configuration of the pair of diodes. There are two different main architectures of sub-harmonic mixers: one uses the diodes in the open loop configuration and the other uses the diodes in anti-parallel configuration. Extensive optimisations have been performed by modifying the geometry of the structure, for instance the length of the anode, the thickness and the width of the substrate, the length and the width of the finger, the dimension of the channel. At the end of that study it appears that the anti-parallel configuration shown in Fig 15 gave better performance. In addition it gives the ability to choose the channel cross section dimensions with much more latitude than with the open loop configuration. The only non compliance to the UMS standard process is the choice of a 50 µm substrate thickness instead of 100 µm. This choice seems to be the best compromise between performance, robustness (too thin substrate would produce warpage and would easily break) and feasibility.

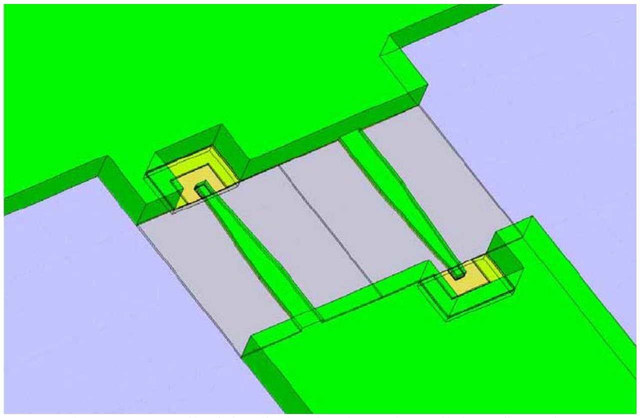


Figure 15: Detail of the diodes for the anti parallel configuration

183 GHz receiver design

It is necessary to create an electrical model of each independent part of the mixer (The LO and RF waveguide to micro-strip transitions, the pair of diodes) and create a global model of the mixer by connecting the independent parts in a proper way in ADS. The electrical models of the independent parts of the mixer are no more than S-parameter matrixes calculated by HFSS. In the global ADS model, a certain number of elements can be optimised: the position of the waveguide backshorts; the length of the different sections of the LO and RF filters.

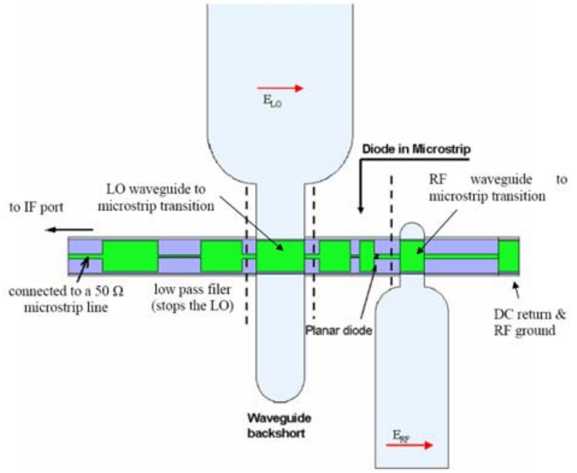


Figure 15: Final topology of a 183 GHz fixed tuned sub harmonic mixer.

The final mixer topology shown in Fig 15 is split in the E plane of the RF and LO waveguides, thus simplifying the assembly of the mixer and reducing waveguide losses. The planar diodes are integrated on a 50 µm thick GaAs circuit containing the embedding circuitry and suspended in a micro-strip channel. Inside this channel, only a quasi TEM mode can propagate. The micro-strip channel is perpendicular to the RF and LO waveguides. Two sided waveguide to micro-strip transitions are used to couple both the RF and LO signal into the channel. The micro-strip metallization bridges across each guide; third height waveguide were used for both the RF and LO rectangular waveguides. Two band-pass micro-strip filters are used to prevent the RF signal from coupling to the LO waveguide and a short-circuited half-wave stub is used to provide the LO termination.

Preliminary results

The LO power coupling for this mixer was optimised at 183 GHz and this mixer required 1.5-2 mW of LO power. The expected mixer DSB conversion losses are about 3 dB and the noise equivalent temperature T_{mix}(DSB) is 180 K. A margin of 2 dB takes into account losses introduced by the external feed horn and mismatches between the mixer and the low noise amplifier (LNA). If the LNA equivalent noise temperature is T_{LNA}=100 K, then the expected DSB receiver noise temperature is about 500 K i.e. at the state-of-the-art. Fig 16 and 17 show a sweep of the RF frequency for the 183 GHz sub-harmonic mixer.

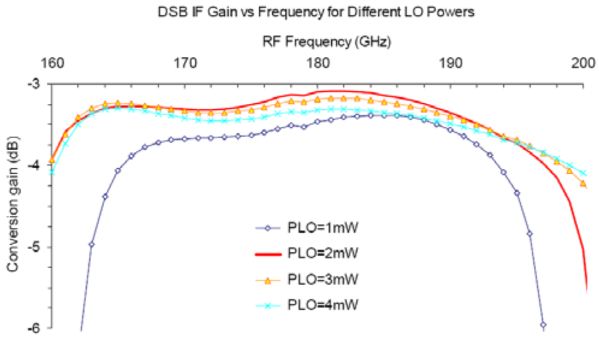


Figure 16: SSB conversion loss dependence versus the LO power

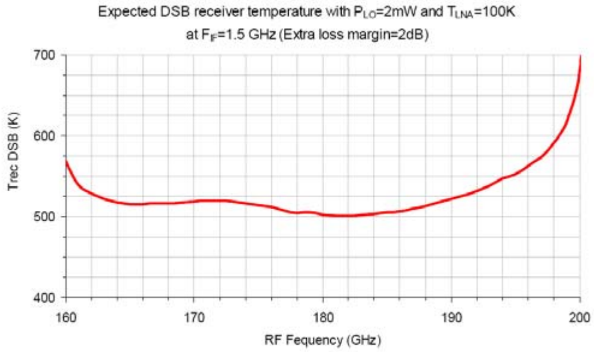


Figure 17: Estimated receiver DSB noise temperature depending on RF frequency

During the next step of the study, single diodes, 183 GHz and 380 GHz will be realised and tested.

VI. CONCLUSION

All these actions, based on the use of industrial foundry with no or minor modifications are aimed at providing a complete set of design available for any potential science mission for Earth or planetary observatory. The feasibility is demonstrated with the current applications MARFEQ and AltiKa where the gain in mass, volume, consumption, NF performances and stability are obvious for K and Ka band receivers. The two other on going actions will permit to cover all the frequency band of interest with the same benefit in the next few years.