A 380 GHz sub-harmonic mixer using MMIC foundry based Schottky diodes transferred onto quartz substrate

J. Treuttel, B. Thomas, A. Maestrini, H. Wang, B. Alderman, J.V. Siles, S.Davis, T.Narhi.

***Abstract*—In this paper, we report upon the development of a 380 GHz sub-harmonic mixer using foundry planar Schottky diodes. The device has been fabricated by the commercial foundry UMS (United Monolithic Semiconductors) using the BES process, and post-processed afterwards to transfer the GaAs circuit membranes onto a quartz substrate. The measurement of a single device has been done with a fast automatic Y factor test bench, with a resolution of 0.001 dB.**

***Index Terms*—Schottky diode, transferred substrate, sub-harmonic mixer, 380 GHz.**

I. INTRODUCTION

While visible and infrared observations from geostationary satellites are available for already three decades and provide only information on the top of the clouds, sub-millimeter wave radiometry offers new perspectives for the characterization of clouds and rain at global scale.

Indeed, recent theoretical studies on the atmospheric sounding capabilities of space borne sub-millimeter wavelengths have shown that cloud content, cloud profile, rain detection and quantification, as well as properties of ice particles, can be derived from brightness temperatures simultaneously measured at different frequencies above 100 GHz with multi-channel retrieval algorithms [1].

Sub-millimeter technology also offers the possibility to deploy a geostationary sensor that would monitor continuously the evolution of the clouds at an adequate spatial resolution. Schottky-diode-based radiometers are highly interesting because of their capabilities to work at ambient temperature and to operate with a fast response.

A MMIC sub-harmonic 380 GHz mixer could then be used to measure the radiometric signal in the 380 GHz H2O band required in the Geostationary Observatory for Microwave Atmospheric Sounding (GOMAS) mission [2]. Additionally MMIC technology based components are more reproducible and could bring the instrumentalists forward to build multi-pixel receivers [3] that would offer new scan strategy for Earth observations.

In this context, the European Space Agency ESA has initiated a programme to investigate the use of the GaAs foundry service from United Monolitic Semiconductor UMS and push forward the limitations of this service for frequencies up to 1 THz [4]. In order to enhance device performance, and particularly reduce dielectric constant and improve thermal conductivity, an amended way of post processing GaAs wafers has been explored [5]. We will report on the design and performance of a 380 GHz sub-harmonic mixer with integrated Schottky diodes fabricated using this process.

A. A high frequency MMIC industrial fabrication process

1) Purposes of development : Schottky diodes are generic components that are used in practically all non-cryogenic millimeter and submillimetre wave receivers in Earth observation and space science. MMIC technology applied to integrated Schottky structures has nevertheless not been conducted by industry at submillimeter ranges. This program consists in demonstrating that MMIC devices could be developped with existing industrial processes enhanced by a transfer substrate technique. The circuit presented this paper has been fabricated by UMS using an amended BES process.

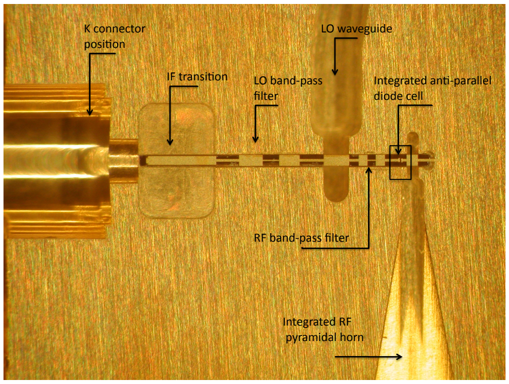

Fig. 1. Picture of the 380GHz mixer placed inside the lower half of the waveguide cavity.

Two fabrication runs have been planned to correct possible diode fabrication default of the first prototype run.

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J.Treuttel and H. Wang are with Observatoire de Paris, LERMA, 75014 Paris, FRANCE and STFC, Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK. E-mail: jeanne.treuttel@obspm.fr

B.Thomas is with Rutherford Appleton Laboratory, Didcot, OX11 0QX and now with Jet Propulsion Laboratory, California Institute of Technology, Passadena CA 91109,USA.

A.Maestrini is with Observatoire de Paris, LERMA, 75014 Paris and Universite Pierre et Marie Curie Paris 6.

B.Alderman is with Rutherford Appleton Laboratory, Didcot, OX11 0QX.

J.V. Siles is with Universidad de Politecnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain.

S.Davis is with University of Bath, Bath, BA2 7AY, UK.

T.Narhi is with ESA/ESTEC, Keplerlaan1, 2200 AG Noordwijk ZH, The Netherands.

2) Transferred substrate technique: A novel yet straightforward transferred substrate technique is described in detail in [5]. This technique does not involve high temperatures and/or high pressures operation, which is very important to avoid circuit degradation. In particular, an etchtop layer was introduced to facilitate membrane formation. This developement for MMIC devices allows the transfer of large surfaces of GaAs membranes (typically 0.7 x 0.7 cm2) onto a wide variety of host substrates. In the case of the circuit presented in this paper, quartz was used.

B. Mixer design

The circuit design of a 380 GHz fixed-tuned MMIC subharmonic mixer similar to [6] is presented hereafter. In particular, the sub-harmonic mixer features an anti-parallel pair of BES planar Schottky diodes integrated with the passive microstrip circuit onto a 4-um thick GaAs membrane.

The GaAs membrane is then transferred onto a 50-um thick quartz substrate using the transferred substrate technique. A gold beam-lead is formed at the RF end during the circuit fabrication, providing precise grounding of the diode pair at IF/DC frequencies. The LO/RF waveguides, the microstrip channel and the IF connector socket are milled into two split-waveguide metal blocks. The circuit placed inside the lower half of the waveguide cavity is shown in Fig.1.

The methodology used to design and optimize the mixer circuit uses a combination of linear/non-linear circuit simulations (Agilent ADS) and 3D electro-magnetic simulations with Ansoft and HFSS.

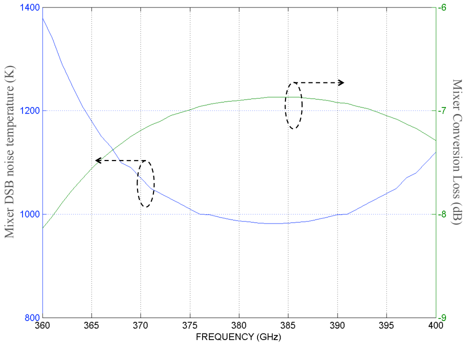

Fig. 2. Simulated conversion loss and mixer noise temperature in the 360-400 Ghz frequency band.

The electrical parameters of the BES Schottky diode model considered in the simulations are a series resistance Rs = 11 Ω, an intrinsic zero voltage junction capacitance of Cjo = 1.7 fF, a saturation current Isat = 50 fA, an ideality factor = 1.25 and a built-in potential Vbi = 0.8 V. Fig.2 shows the estimated DSB conversion losses of the mixer versus RF frequency. A local oscillation power of 2.5 mW is assumed during the simulations. An IF frequency of 1.5 GHz is chosen. The estimated DSB mixer noise temperature is bellow 1000 K around 380 GHz, and bellow 1200 K between 360 GHz and 400 GHz. The instantaneous RF/LO bandwidth is predicted to extend over a relative bandwidth of more than 10 percents.

C. First run results

I/V measurements of several anti-parallel pair of diodes have been performed at the Rutherford Appleton Laboratory(RAL) and show unsymmetrical diode characteristics. For example the serie resistance have been measured as Rs_{Diode1} = 19.88 Ω and Rs_{Diode2} = 40.4 Ω, the ideality factor as η_{Diode1} = 1.26 and η_{Diode2} = 1.39 and the saturation current as Is_{Diode1} = 1.55 e-14 A and Is_{Diode2} = 7.55 e-14 A. These first run I/V results affect the mixer predicted performance.

Preliminary measurements of the mixer noise temperature done at the Observatory of Paris (LERMA) are given in Fig.3. The mixer presents a double sideband noise temperature of 3667 K and 10.9 dB of conversion loss at 390 GHz. The experimented results are for one single device only and are a outcome of the first prototype farication run. Two others mixers are expected to be tested in the future for the second run.

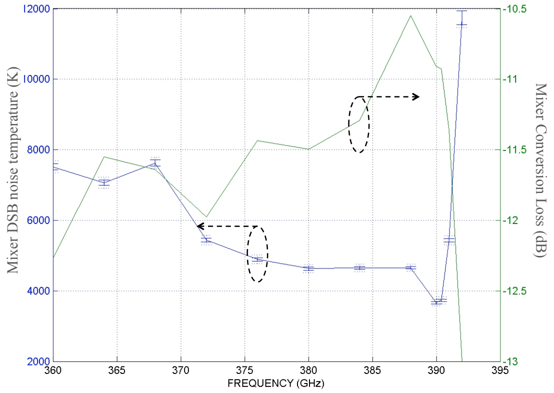

Fig. 3. Mixer characterisation results done at LERMA. Left-hand side curve: DSB mixer noise temperature(K), Right-hand side curve: conversion loss(dB). Worth case and quadratic errors bars are plotted for the DSB mixer noise temperature for load temperatures uncertainty of 0.5 (hot load) and 3 K (cold load).

D. LERMA mixer measurement set up

1) Measurement procedure: The G_{Mix} and T_{mix} are deduced from consecutive measurements of T_{Rec} and T_{IF} with an internal noise diode switched on and off as follow:

$$T_{IFon} = \frac{T_{hot} - Y_{IFon} * T_{cold}}{Y_{IFon} - 1} \tag{1a}$$

$$T_{IFoff} = \frac{T_{hot} - Y_{IFoff} * T_{cold}}{Y_{IFon} - 1} \tag{1b}$$

By substracting (1a) and (1a) and injecting it into the respective Friis formula, we deduce (2a) and (2b).

$$G_{mix} = \frac{T_{IFon} - T_{IFoff}}{T_{RECon} - T_{RECoff}} \tag{2a}$$

$$T_{mix} = T_{RECoff} - T_{IFoff} * \frac{T_{RECon} - T_{RECoff}}{T_{IFon} - T_{IFoff}} \tag{2b}$$

This straight forward operation allow us to deduce the gain of the chain with local and time related measurements.

2) Measurement error: The quadratic error of the meaurement chain, i.e. mixer noise temperature ΔT_{Mix} and gain ΔG_{Mix} have been calculated from the uncertainty budget element taken as the measurement error $\Delta Y_{reading}$ and load temperature error ΔT_{cold}, ΔT_{hot} . Because the error depends on the different derivative value, the contribution on each parameter error will not be homogenous. We note that the final error is drastically depending on mixer absolute noise temperature and conversion loss. For this purpose we have descibed the uncertainty of the measurement for different mixer performance in table I. We take for the hot and cold load an error of respectively 4 % and 0.5 %.

T_{Mix}-G_{Mix}	$Y_{reading}$	Quadratic error (ΔT_{Mix}-ΔG_{Mix})
683K - 0.3717	0.115 %	1.32 % - 2.58 %
3667K - 0.0812	0.5 %	1.745 % - 4.18 %
11740K - 0.0501	1 %	3.32 % - 14.77 %

TABLE I
UNCERTAINTY OF THE OVERALL MEASUREMENT CHAIN FOR A GIVEN MIXER PEFORMANCE IN PERCENTAGE

For the presented mixer, we have a quadratic error of 1.32 % (64 K) for ΔT_{Mix} and 4.18 % (0.0034) for ΔG_{Mix} at 390 GHz. Two set of error bars, quadratic and worth case are plotted in Fig.3 for each frequency points.

3) Description of the test bench: The setup is mounted on top of an optical table and uses multiple opto-mechanical parts from Newport to firmly fix the mixer, the Local Oscillator (LO) chain and the Intermediate Frequency (IF) amplifier chain to the bench. The IF 2-4 GHz chain amplifies the output signal of the mixer with a gain of 77 dB. The power meter (N1912A and a fast power sensor Agilent E9325) is externally synchronized with a mechanical chopper used to present alternatively a blackbody at room temperature and a blackbody at 77 K in front of the mixer feed horn. Chopper frequency is set to 33 Hz.

4) IF chain: In addition to classical Y factor measurement chain, LERMA IF chain has an internal noise source that can be switched on and off to modify its noise factor.This feature is very useful since two independent Y-factor measurements are necessary to extract both the equivalent noise temperature of the mixer and its conversion losses. The IF chain is integrated on an aluminum box (see Fig.4).

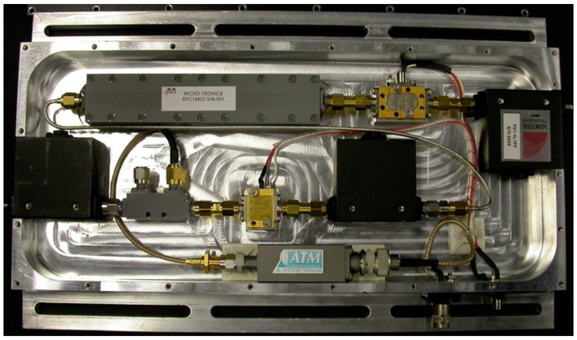

Fig. 4. 2-4 GHz IF chain with internal noise diode described in [7].

5) Power sensor and power meter setup: Our mixer bench uses an Agilent N1912A power meter and an Agilent E9325A peak power sensor for measuring the power delivered by the IF chain. Two time gates are defined on the N1912A power meter : one corresponds to the room temperature black body being totally in front of the mixer feed horn, the other corresponds to the 77 K black body being totally in front of the mixer feed horn. The Agilent E9325A peak power sensor is configured in normal mode and bandwidth is set to off. The power meter measures in Feed1 the average power of gate1 while feed2 records the average power of gate2. A combined measurement can be defined as Feed1/Feed2 which is the uncorrected value of the Y-factor. The power meter gives directly an uncorrected value of the Y-factor with a resolution of 0.001dB and a noise floor of 0.001 dB after video averaging over 256 periods.

6) Agilent E9325A peak power non-linearity corrections: As the Agilent E9325A power sensor has only 300kHz of bandwidth it is not calibrated for measuring white noise signals of several gigahertz of bandwidth. It is necessary to calibrate the power sensor against a sensor with unlimited bandwidth like the Agilent 8482A thermocouple sensor. Our calibration procedure is able to correct the Y-factor with an estimated remaining non-linearity error below 0.005 dB/dB. For white noise signals in the 2-4 GHz band and for powers ranging from -5 dBm to -1 dBm, the uncorrected Y factor is biased by a systematic error of +0.097 dB/dB. For power in the -10 dBm to -5 dBm, the uncorrected Y factor is biased by a systematic error of +0.093 dB/dB. Note that the non linearity of the E9325A sensor decreases if it is configured in average only mode but in this case time gating is not available.

II. CONCLUSION

A 380 GHz sub-harmonic mixer has been fabricated with a new transferred substrate process using MMIC industrial process and avoiding high pressure and temperature. The device shows performances affected by diode unexpected characteristics. Other devices fabrication and test are on-going for a second run expecting better diode performances. This first attempt to use UMS process at these frequencies is very promising for MMIC fabrication at industrial scale adding a simple transfer substrate process. We expect this technique to be developped in the future for multipixel Schottky receivers. The mixer has been tested with a Y factor mixer characterisation test bench built at LERMA observatory of Paris. The Y factor has a resolution of 0.001 dB and an estimated remaining non-linearity error below 0.005 dB/dB. The quadratic error is depending on absoulte mixer performance.

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