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


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 Monolithic 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 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 developed 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.

A. A high frequency MMIC industrial fabrication 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.
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 development 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 sub-harmonic 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.

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 $R_{s,Diode_1} = 19.88 \, \Omega$ and $R_{s,Diode_2} = 40.4 \, \Omega$, the ideality factor as $\eta_{Diode_1} = 1.26$ and $\eta_{Diode_2} = 1.39$ and the saturation current as $I_{s,Diode_1} = 1.55 \, \text{e-14 A}$ and $I_{s,Diode_2} = 7.55 \, \text{e-14 A}$. 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 fabrication run. Two others mixers are expected to be tested in the future for the second run.

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 $R_s = 11 \, \Omega$, an intrinsic zero voltage junction capacitance of $C_{j0} = 1.7 \, \text{fF}$, a saturation current $I_{sat} = 50 \, \text{fA}$, an ideality factor $\eta = 1.25$ and a built-in potential $V_{bi} = 0.8 \, \text{V}$. 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.

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:

$$T_{IFon} = \frac{T_{hot} - Y_{IFon} \ast T_{cold}}{Y_{IFon} - 1} \quad (1a)$$

$$T_{IFoff} = \frac{T_{hot} - Y_{IFoff} \ast T_{cold}}{Y_{IFoff} - 1} \quad (1b)$$

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

$$G_{mix} = \frac{T_{IFon} - T_{IFoff}}{T_{RECoff} - T_{RECoff}} \quad (2a)$$

$$T_{mix} = T_{RECoff} - T_{IFoff} \ast \frac{T_{RECoff} - T_{RECoff}}{T_{IFon} - T_{IFoff}} \quad (2b)$$

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 measurement chain, i.e. mixer noise temperature $\Delta T_{\text{Mix}}$ and gain $\Delta G_{\text{Mix}}$ have been calculated from the uncertainty budget element taken as the measurement error $\Delta Y_{\text{reading}}$ and load temperature error $\Delta T_{\text{load}}$, $\Delta T_{\text{hot}}$ . 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 described 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 %.

![Table I: Uncertainty of the overall measurement chain for a given mixer performance in percentage](image)

For the presented mixer, we have a quadratic error of 1.32 % (64 K) for $\Delta T_{\text{Mix}}$ and 4.18 % (0.0034) for $\Delta G_{\text{Mix}}$ 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 E9325A) is externally synchronized to the 77 K black body being totally in front of the mixer feed horn. Chopper frequency is set to 33 Hz. 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 an estimated remaining non-linearity error below 0.005 dB/dB. The quadratic error is depending on absolute mixer performance.

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REFERENCES


