A 530-600 GHz silicon micro-machined integrated receiver using GaAs MMIC membrane planar Schottky diodes

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Abstract— **We present here a novel integrated receiver architecture called Radiometer-On-a-Chip (ROC) that uses a combination of MMIC amplifier, GaAs Schottky multiplier and mixer devices and silicon micro-machining techniques. The novel stacking of micro-machined silicon wafers allows for the 3-dimensional integration of the W-band power amplifier, a 280 GHz tripler and a 560 GHz sub-harmonic mixer in an extremely compact package. Preliminary results give a DSB mixer noise temperature of 4860 K and DSB mixer conversion losses of 12.15 dB at 542 GHz. Instantaneous 3 dB RF bandwidth extends from 525 to 585 GHz. To the authors' knowledge, this is the first demonstration of an all integrated silicon micro-machined receiver front-end at these frequencies.**

INTRODUCTION

The sub-millimeter wave range (300 GHz – 3 THz) is rich in emission and absorption lines of various molecular species (i.e. CH_4, CO, H_2O, HCN, etc…) whose detection and mapping are important to understand the atmospheric circulation of telluric planets (Venus, Earth, Mars), outer planets (Jupiter, Saturn) and their moons (i.e. Europa, Titan). Sub-millimeter wave spectrometers with very high spectral resolution have been flown for Earth remote sensing up to 2.5 THz. However, their use in planetary exploration has been severely restricted due to their large mass and power requirements. Conventional approach prevents them from fitting in the mass and power budgets of most platforms.

To tackle that problem, we present here a novel Radiometer-On-Chip (ROC) architecture that uses a combination of GaAs MMIC Schottky diodes and silicon micromachining techniques. Due to the unique arrangement of actives components together with silicon micro-machined waveguide structure in a stacked configuration, three-dimensional radiometer circuits can now be conceived and are presented here. First, a W-band amplifier module based on this technology utilizing pHEMT based MMICs has been designed, fabricated and tested. The design of the Si-packaged amplifier is shown here. Second, the development of an integrated 530-600 GHz silicon micro-machined ROC is discussed later. The 530-600 GHz ROC features an integrated 265-300 GHz tripler and 530-600 GHz sub-harmonic mixer based on MMIC GaAs membrane planar Schottky diodes. Preliminary measurement results are presented. This novel approach allows the reduction of the heterodyne receiver front-end elements (Local Oscillator generation based on frequency multiplication/amplification, sub-harmonic and/or fundamental mixers, IF Low Noise Amplifiers and DC bias circuits) by an order of magnitude in mass compared to conventional metal milling.

ROC ARCHITECTURE CONCEPT

The ROC architecture is based on the stacking of Silicon micro-machined wafers together with MMIC GaAs devices, and is shown in Fig.1. Two stages can be identified: the 1st one including components operating at W-band and the second one for the 300-600 GHz components. The first stage is made of the 1st and 2nd Si-layer. It includes a W-band Power Amplifier (PA) MMIC device in between. The 2nd wafer also act as a spacing layer between the first stage (PA) and the third stage. The second stage is made of the 3rd and 4th Si-layer. It includes a 265-300 GHz MMIC GaAs membrane Schottky tripler and a 530-600 GHz MMIC GaAs membrane Schottky sub-harmonic mixer in between. Each layer interfaces with the next one through waveguides opening on the flat of the Si wafers. The LO signal is input via a W-band input waveguide. The RF signal is input via an RF feed-horn. The IF signal is output via a micro-coaxial connector on the top of the 4th layer.

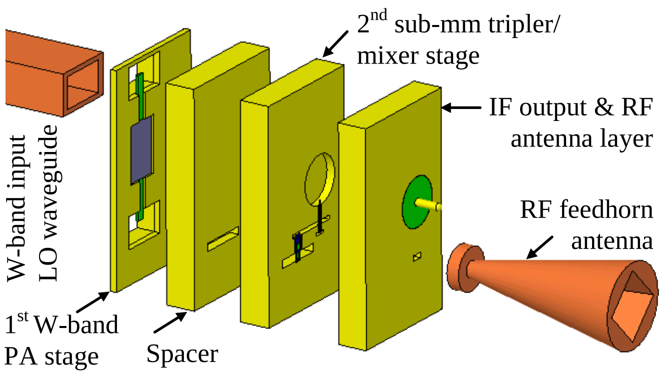

Fig.1. Radiometer-On-a-Chip concept, including an input W-band waveguide, a W-power amplifier stage, an integrated 300 GHz tripler - 600 GHz sub-harmonic mixer stage, and a 600 GHz RF feed-horn antenna.

Although this approach is meant to integrate both stages at the same time, each stage has first been designed and implemented individually in order to characterize them separately. Therefore, in the following sections, additional Si-layers are used for each stage in order to interface them with standard metal waveguide flanges required for testing.

DESIGN OF A W-BAND POWER AMPLIFIER

First, a W-band Power Amplifier MMIC based on GaAs pHEMT technology is packaged in a novel silicon micro-machined block. The MMIC devices are similar to the one previously used in classical metal packages [1]. These MMIC devices are interfaced with W-band waveguide via H-plane probe transitions described in [2]. These transitions are chosen to have the input/output waveguide interfaces with external waveguides on the flat surface of the wafers as shown in Fig.1. However, in order to use common screw holes and dowel pin holes of standard waveguide flanges (UG387) for the input and output waveguides, it is necessary to re-align the input/output waveguides of the amplifier module. For that purpose, two waveguide H-bends derived from [3] are used at the input and output. One-step H-bends are chosen instead of two-steps bends described in [3] mainly for ease of fabrication. It has been shown using 3-D electromagnetic simulations (HFSS [4]) that the return losses of the transition from the microstrip lines to the input/output waveguides including the double bends are below -12 dB between 75 and 108 GHz, which is acceptable for W-band amplifier stage. The resulting 3-D hollow waveguide and channel structures is shown in Fig.2. They are shown together with the split lines of the four Si-wafer used.

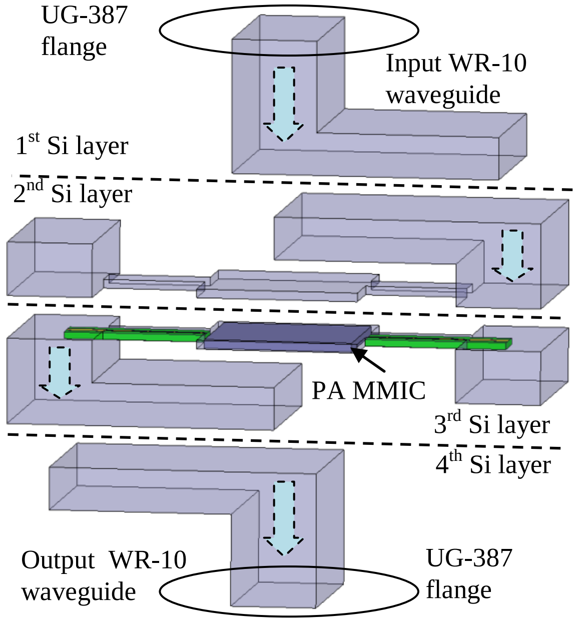

Fig.2: 3-D view of the W-band Si micro-machined Power Amplifier stage showing the hollow waveguide and channel structure (left hand side), and the four silicon micro-machined layers constituting the module and including a UG-387 flange for the input and output waveguides connections.

The final W-band Si PA module is shown in Fig.3. The overall dimensions are 20 x 25 x 4 mm^3. It weighs less than 5 grams. As presented in a companion paper [5], the performance is similar to a metal packaged amplifier module using the similar devices. A typical output power between 30 and 80 mW has been measured between 92 and 104 GHz.

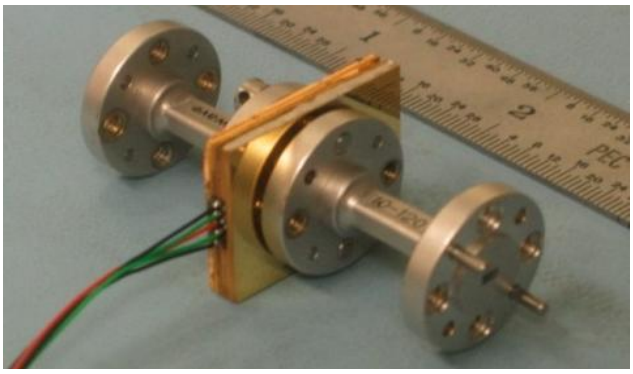

Fig.3: Photo of an W-band Si micro-machined power amplifier module with integrated DC bias board. The dimensions of the Si part are 20x25x4 mm^3.

A 530-600 GHZ INTEGRATED TRIPLER/SUB-HARMONIC MIXER

The second stage of the ROC is an integrated 265-300 GHz tripler and 530-600 GHz sub-harmonic mixer using MMIC planar Schottky diode devices.

A view of the second stage is shown in Fig.4. It is made of four micro-machined silicon layers stacked on top of each other (only the 2 bottom layers are visible in Fig.4). The tripler W-band input waveguide and 560 GHz RF input waveguide are aligned to use common screw holes and dowel pin holes of the UG-387 flanges, as previously described for the PA stage. Additional 1 mm diameter holes are included as dowel pin holes to align the four silicon layers precisely. K-type glass beads are used for the DC connection of the tripler, and the IF connection of the mixer. The IF microstrip to K-connector transition is taken from [6]. The only modification is that an SSMA flange launcher connector is used instead of a K flange launcher to reduce the footprint on the Si-wafer. A 2-10 GHz IF impedance matching circuit on AlN substrate is also included between the mixer and the output connector. It allows one to match the high impedance of the mixer diodes to the 50 Ω impedance of the 1st LNA.

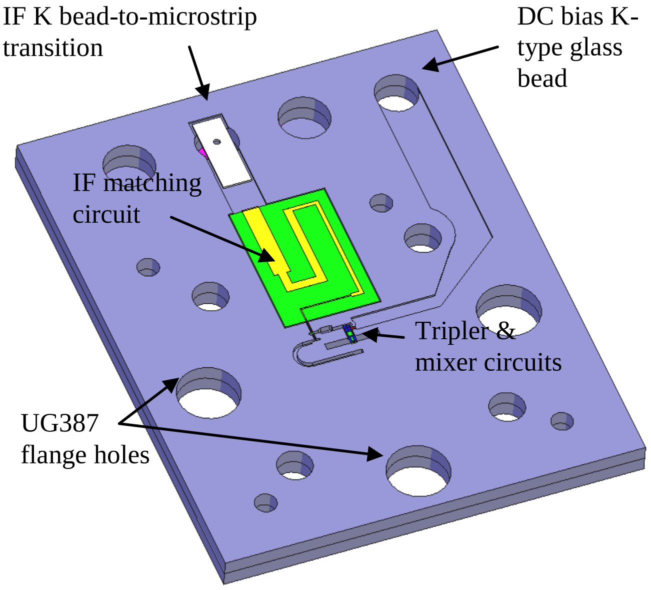

Fig.4: 3-D view of the two bottom layers of the integrated 280 GHz tripler/ 560 GHz sub-harmonic mixer stage of the ROC. It includes DC and IF K-type connectors for the tripler bias and mixer IF output, an 2-10 GHz IF matching circuit, and two tripler and sub-harmonic mixer MMICs.

The 300 GHz MMIC Schottky device used for the tripler has been described previously [7]. In order to adapt it to the Si micro-machining architecture, the input and output waveguide matching network has been re-designed. As a result, the nominal operating bandwidth of the tripler is re-tuned for 265-310 GHz, compared to the initial 260-340 GHz bandwidth [7]. The 530-600 GHz sub-harmonic mixer features a GaAs membrane MMIC device with a pair of planar Schottky diodes arranged in balanced configuration, as described in [8]. The MMIC sub-harmonic mixer (SHM) is biasless. Details about the simulation procedure employed for the design of the 280 GHz tripler and the 560 GHz sub-harmonic mixers can be found in [9][10]. Both devices are first simulated separately, and then simulated together in ADS to compute the overall performance and maximize the matching between the tripler and mixer stage at LO frequencies (265-300 GHz). Detailed view of the 280 GHz tripler/ 560 GHz sub-harmonic mixer circuit is shown in Fig.5. As shown in Fig.5, the W-band input LO signal enters from the top and the RF signal enters from the bottom of the Silicon wafers stack.

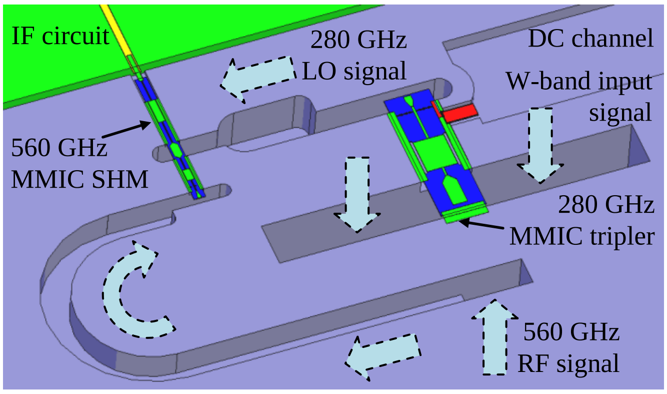

Fig.5: Detailed 3-D view of the 280 GHz tripler / 560 GHz sub-harmonic mixer stage. The tripler is a balanced 6-anodes GaAs Schottky MMIC similar to [7]. The sub-harmonic mixer is a balanced 2-anodes GaAs membrane Schottky MMIC scaled from [8].

Simulations show that an input power between 2 mW and 3 mW is enough to pump the mixer, and that 30-50 mW of input power at W-band is necessary to pump the combined tripler/mixer.

Tripler/mixer stage fabrication

The second stage of the ROC has been fabricated using DRIE micromachining techniques to etch the waveguides and channels in four 750 µm thick silicon layers. The details of the fabrication process are described in a companion paper [5]. The Silicon layers, once etched, are gold plated. Devices are mounted on the two bottom layers. Due to the fact that the RF waveguide is opened in the bottom, it is possible to precisely align optically the RF feed-horn with the RF waveguide opening of the two bottom Si layers and glue it in place before closing the Si block. A photo of the mounted second ROC stage is shown in Fig.6. As illustrated in Fig.6, the four Si layers are sandwiched between the W-band input LO waveguide and the 560 GHz RF feed-horn antenna. The feedhorn antenna used for the test is a corrugated type. A small additional plate on the back of the wafers (the W-band input side) allows to press the SSMA connector flat on the front side of the wafers (RF input side).

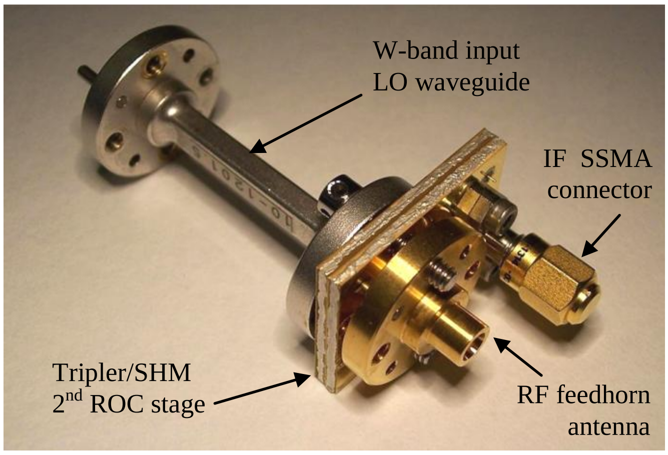

Fig.6: Photo of the second stage of the ROC, including 280 GHz tripler and 560 GHz sub-harmonic mixer MMICs. It also includes an SSMA IF connector and K-type glass bead DC bias connection. The overall dimensions of the Si block are 20x25x3 mm^3.

The overall dimensions of the silicon micromachined tripler/mixer stage is 20x25x3 mm^3. Without the feedhorn, SSMA and input waveguide, it weighs less than 5 grams.

Preliminary test results

Preliminary tests on the second stage of the ROC are very encouraging. The tripler/mixer stage is pumped with an Agilent W-band source and a classical driver/power amplifier stage. The IF output is fed into an automatic mixer measurement IF amplification and detection test set-up. A classical Y-factor measurement was performed using a room temperature and liquid nitrogen cooled calibration load. The IF bandwidth is 30 MHz centered around 4 GHz. No correction for IF mismatch was included.

Preliminary test results give a DSB mixer noise temperature of 4860 K and DSB mixer conversion losses of 12.15 dB at 540 GHz center RF frequency. The 3 dB instantaneous RF bandwidth extends from 525 to 585 GHz. The amount of input power necessary at W-band to pump optimally the mixer is measured between 30 and 50 mW, in accordance with the predictions.

It is expected that the performance of the ROC will improve with a better control of the surface roughness of the waveguides.

A 560 GHz COMPLETE ROC FRONT-END

A complete silicon micro-machined ROC module including the first W-band PA stage and the second tripler/mixer stage has been assembled and is shown in Fig.7. The overall dimensions of this front-end is 25x25x8 mm^3 for the silicon parts, and weighs less than 10 grams. This corresponds to a reduction of approximately 50 in size and mass compared to traditional metal machined receiver front-ends.

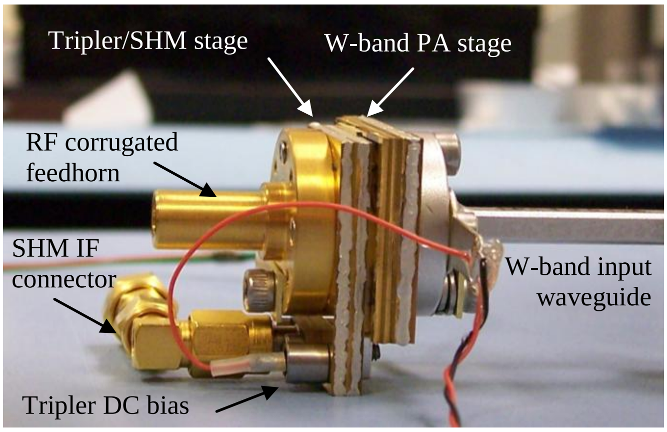

Fig.7: Photo of a fully assembled ROC front-end module, including the silicon micro-machined PA and tripler/mixer stages. The overall dimensions of the silicon parts of the ROC is 25x 25x8 mm^3.

Tests are on-going in order to fully characterise this ROC front-end module.

CONCLUSIONS

As a proof-of-concept, a silicon micro-machined W-band amplifier module and a 530-600 GHz integrated sub-harmonic mixer/tripler based on the same approach have been demonstrated. This novel silicon-based architecture allows for the 3-D integration of amplifier, multiplier and mixer MMICs in a extremely small package. This architecture is also readily extendable to two dimensional array of receivers, paving the way for the development of large focal plane array type instruments. This novel architecture is expected to reduce the size, mass and power consumption of heterodyne receivers onboard future missions dedicated to the remote sensing of planets' atmospheres and surfaces, as well as for astrophysics.

ACKNOWLEDGMENT

The authors wish to acknowledge the help and support of Dr. Peter Siegel. We also would like to thank Dr. Alain Maestrini for providing very useful information concerning the design of the tripler.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract from the National Aeronautic and Space Administration.

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