Development of a 340-GHz Sub-Harmonic Image Rejection Mixer Using Planar Schottky Diodes

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***Abstract*— : We report on the design, fabrication and test of an integrated 320-360 GHz Sub-Harmonic Image Rejection Mixer (SHIRM) using planar Schottky diodes. The integrated circuit uses two separate anti-parallel pairs of diodes mounted onto a single quartz-based circuit. Measurement results give SSB receiver noise temperatures of 3300 K at 340 GHz, with an image rejection from 7.6 dB to 23 dB over the entire band.**

***Index Terms*— Image rejection mixer, sideband separation, sub-harmonic mixer, planar Schottky diodes.**

I. INTRODUCTION

Space-borne sub-millimetre wave atmospheric limb observations can give unique insights information on the global distributions of key molecular species in the Earth's upper troposphere and lower stratosphere (e.g., the STEAM-R proposal [1]). In order to best resolve the limb emissions from rotational and vibrational lines in the troposphere, it is necessary to separate the receiver sidebands. Previous air-borne limb sounding instruments have used Frequency Selective Surfaces (FSS) in the mixer's field-of-view the optical path to reject the upper unwanted side band [2].

In parallel, similar requirements in radio-astronomy have lead during the past decade to the development of efficient SIS sideband separating mixers. They have now been chosen, for example, as the generic receiver architecture for most of the ALMA receiver bands, from 100 GHz up to 700 GHz [3]. Until now, this approach had not been applied to Schottky diodes mixers in this frequency range. However, in the recent years, the development of a Sub-Harmonic Image Rejection Mixer (SHIRM) using pHEMT semiconductor diodes has been successfully demonstrated in Q-band [4], from which the name of the device described here is taken.

We present in this paper the design and development of an integrated 320-360 GHz Sub-Harmonic Image Rejection Mixer (SHIRM) that uses planar Schottky diodes. Measurement results of a prototype are reported and compared with the performance of a more traditional Single Side Band (SSB) receiver featuring a DSB mixer and a Frequency Selective Surface.

II. 340 GHZ SUB-HARMONIC IMAGE REJECTION MIXER ARCHITECTURE

The 340 GHz Sub-Harmonic Image Rejection Mixer (SHIRM) design concept uses two double side band (DSB) sub-harmonic mixer circuits connected at the RF frequencies by a 3 dB in-phase power splitter, and at the Local Oscillator (LO) frequencies by a 45° phase shifter and 3 dB power splitter, as illustrated in Fig.1. Similar designs of SSB fundamental mixers show that the quadrature can be performed by phase shifting either the RF signal or the LO signal by 90° [5]. In our case, we have chosen to phase shift the LO signal as the tuning bandwidth required to meet the LO specifications for STEAM-R is reduced (max. 164-171 GHz) compared to the broader RF band (314-356 GHz). As the DSB mixers used here are sub-harmonically pumped at the second order, it is necessary to 45° phase shift at the LO in order to ensure that the IF output signals are phase shifted by 90°. The IF signals from both DSB mixers are recombined afterwards by using a 90° hybrid 3 dB coupler to perform the image rejection of each side band.

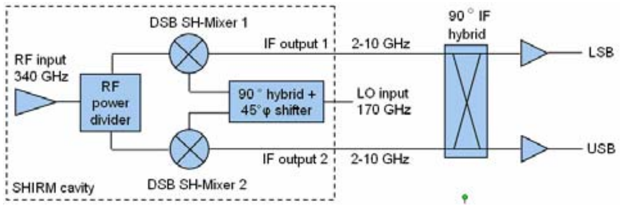

Fig.1. Schematic diagram of the SHIRM. The components in the dotted box are integrated inside a single block. Both IF outputs are recombined externally to the SHIRM block using a commercial 90° IF hybrid 3 dB coupler.

The SHIRM circuit features two DSB sub-harmonic mixer sub-circuits joined together in a single quartz-based microstrip circuit, each one using an anti-parallel pair of planar Schottky diodes, as illustrated in Fig.2. Both sub-circuits are IF/DC grounded at the centre of the single substrate, with the IF output of both mixers coupled via its endings. The LO WR-05 waveguide 45° phase shifter is derived from a previous design described in [6]. It is constituted by a 90° waveguide hybrid 3 dB coupler scaled from a WR-10 design presented in [7], and a 45° stub-loaded waveguide phase shifter. The RF WR-2.8

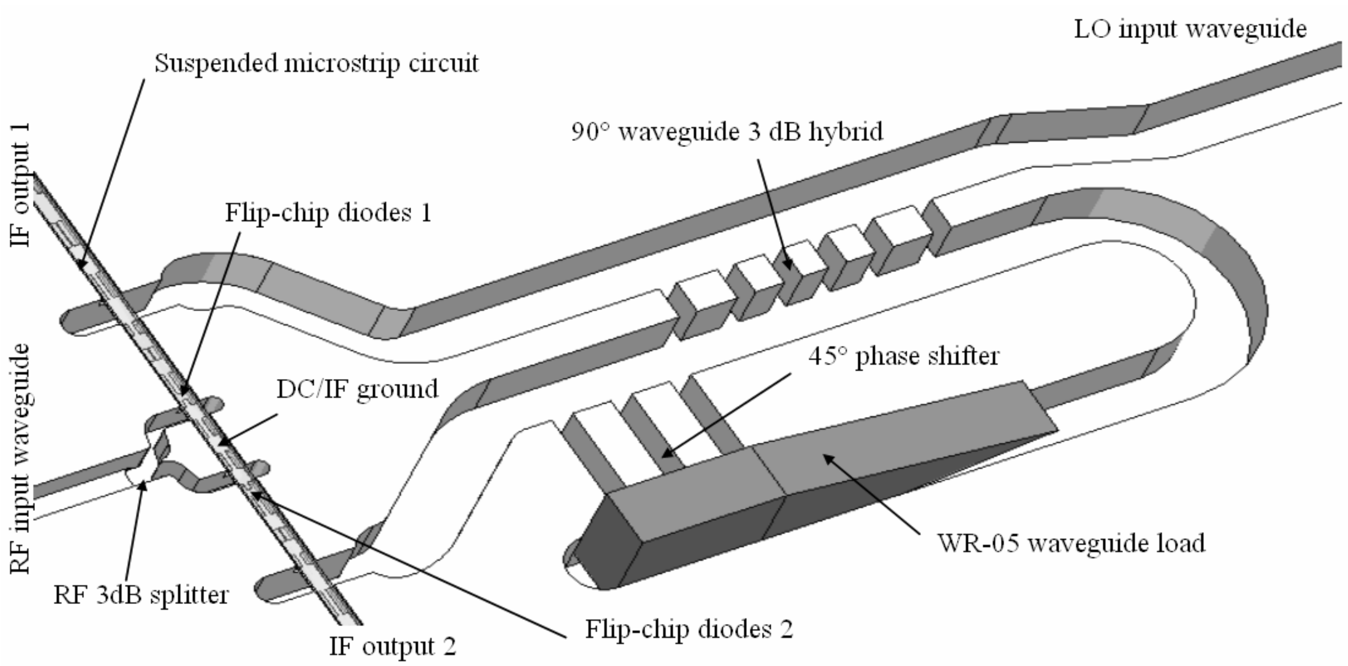

Fig.2. 3D view of the SHIRM, including the inverted suspended circuit and the 3 dB RF power splitter (on the left), the 45° waveguide phase shifter and the LO waveguide load (middle and right). RF input is from 320 to 360 GHz. LO input is around 170 GHz

waveguide 3 dB power splitter is a compact Y-junction divider derived from [8]

III. SHIRM DESIGN

The design methodology uses a combination of linear/non-linear circuit simulations (Agilent ADS [9]) to optimize and compute the performances of the circuit, and 3D EM simulations (Ansoft HFSS [10]) to model accurately the diodes and waveguide structures.

First, each sub-harmonic mixing branch of the SHIRM use an anti-parallel pair of planar Schottky diodes. The electrical parameters considered for these diodes are a series resistance R_s = 15 Ω, a zero voltage junction capacitance of C_{jo}= 1.3 fF, saturation current I_{sat} = 2e-16 A, ideality factor η=1.3 and built-in potential V_{bi} = 0.73 V per anode. Considering an optimum LO power level of 1.5 mW, a set of non-linear simulations gives an ideal embedding impedances of approximately Z_{RF} = 83+j.53 at RF frequencies and Z_{LO} = 147+j.207 at LO frequencies. The IF load impedance is set to 100 Ω, at a frequency of 2.5 GHz. In a second step, each part of the circuit is modelled electromagnetically with HFSS, and imported in ADS for further optimisation. In order to retrieve the S-parameters at the level of each Schottky barrier, micro-coaxial probes are introduced [11]. The 45° waveguide phase shifter is optimised to exhibit minimum phase and amplitude imbalance over the LO frequency range. The simulated performance gives a maximum amplitude imbalance of ± 0.5 dB and a phase imbalance of ± 5° over the frequency range 160-180 GHz.

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The whole SHIRM circuit is optimized for best image rejection and lowest conversion losses in the RF range 320-360 GHz. An typical value of the IF hybrid phase and amplitude imbalances (given by the manufacturer) is taken into account during the optimisation process. The predicted performance of the SHIRM is presented in Fig. 3. The LO power required to pump the SHIRM is estimated at 6 mW.

Average SSB conversion losses of approx. 9 dB and side band ratio better than 20 dB are predicted.

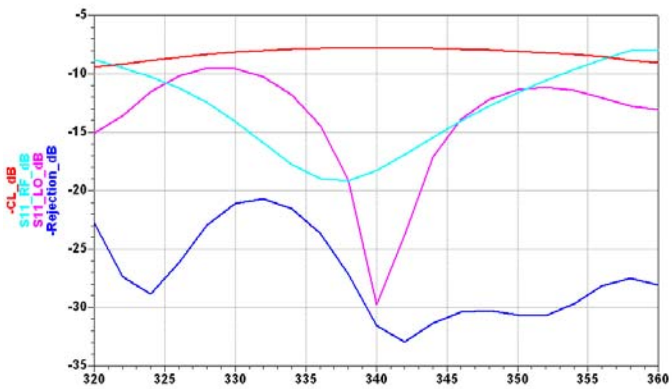

Fig.3. Predicted performance of the SHIRM over the desired RF frequency range, including conversion losses (top red curve), RF and LO input return losses (middle light blue and pink curves), and side band image rejection (lower dark blue curve). LO power is set to 6 mW, IF impedance to 100 Ω.

IV. SHIRM MANUFACTURE AND ASSEMBLY

Two anti-parallel pairs of discrete planar Schottky diodes fabricated at RAL [12] are selected on the basis of similar DC characteristics, flip-chip mounted and soldered onto the RF gold-on-quartz microstrip circuit. Two other IF quartz based microstrip circuits are mounted and glued into the lower half of the split waveguide block. The quartz-based RF stripline circuit is inverted-suspended into the cross-waveguide channel as previously described [13]. It is connected to both IF output circuits by the sides and grounded to the lower half of the block by the middle using silver loaded epoxy glue. A K-type glass bead is then connected to the end of each IF microstrip circuit. Finally, a WR-05 waveguide load scaled from the Type 1 WR-10 design presented in [14] and machined out of MF116 Eccosorb material [15] is inserted inside the waveguide branch connecting the isolated port of the 90° hybrid. The assembled SHIRM block shown in Fig. 4 also includes two K-type flange launcher connectors (on the side), an integrated 330 GHz diagonal horn antenna (visible in front of the block) and a WR-05 UG387 input waveguide flange (on the back, not visible). The dimensions of the SHIRM blocks are approximately 2 cm x 2 cm x 2.5 cm.

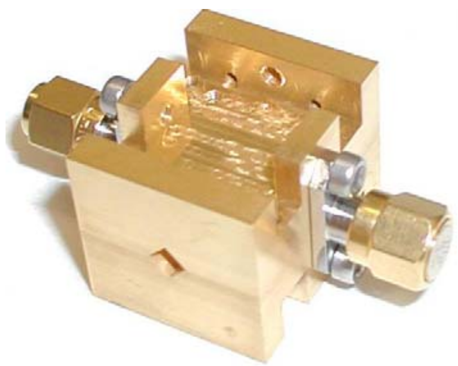

Fig.4. Photograph of the assembled 340 GHz SHIRM block.

V. TEST OF THE SHIRM

The LO source driving the 340 GHz SHIRM comprises a Gunn diode oscillator followed by a rotary vane attenuator and a 166 GHz VDI frequency doubler (Ref. D154 [16]). The output power of the LO chain is calibrated using a PM3 Erickson Calorimeter [17]. Both IF output signals are then fed into a 2-8 GHz commercial IF 90° hybrid coupler (from Krytar™) exhibiting a maximum amplitude and phase imbalance of ± 0.35 dB and ± 3 dB respectively in the band. The IF output signals are then amplified by two low noise amplifier chains with a noise figure of 0.94 dB, each including an isolator and a 2-8 GHz band-pass filter. The output of both chains is alternatively switched to a Gigatronic 8542C power sensor for power measurement, and to a spectrum analyser for spectral line measurement. The test procedure to determine the SSB receiver noise temperature and image rejection is done according to [18]. First, a Y-factor measurement of the receiver is taken to determine the receiver noise temperature using the broadband power sensor. Then, a spectral line is injected into the SHIRM and tuned inside the RF bandwidth. The line is provided by a photo-mixer developed at RAL [19], delivering few nW to the SHIRM at 330 GHz from the beating of two 1.55 μm laser sources. The output IF signal is observed on an Agilent spectrum analyser in a log scale amplitude mode, with resolution bandwidth of 300 kHz and a sample averaging of 50.

Preliminary test results are presented in Fig. 5. These results are uncorrected from the spectrum analyser envelop detector error with log display. The image rejection at a LO frequency of 170 GHz is measured between 7.6 and 23 dB in the frequency range 317.5-362.5 GHz. Best SSB receiver noise temperature of 3300 K has been measured at a centre RF frequency of 340 GHz, with a value lower than 3800 K over the RF frequency range 324-360 GHz. The amount of LO power required to pump the SHIRM is between 7 mW and 11 mW for different LO frequencies.

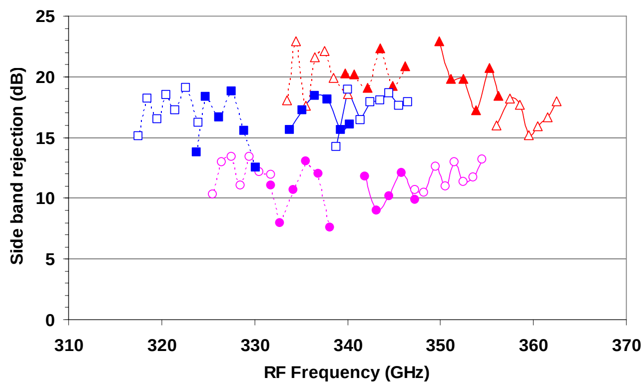

Fig.5. Measured image rejection performance of the 340 GHz SHIRM as functions of the RF frequency. Two IF chains are used: 2-8 GHz (full dots) and 6-14 GHz (empty dots). LSB results are shown with dotted lines, USB with continuous lines. Blue square dots are for an LO frequency of 166 GHz, the pink round dots for 170 GHz, and the red triangles for 174 GHz.

VI. COMPARISON WITH A QUASI-OPTICAL SSB MIXER

The SHIRM performances are compared to a Schottky diode based SSB receiver developed by RAL and ASTRIUM-Portsmouth to upgrade the Band B channel of the MARSCHALS instrument [2]. It features a 295-350 GHz DSB sub-harmonic mixer with integrated 12-24 GHz low noise pre-amplifier and a 310 GHz FSS developed by Queens University Belfast (QUB) [20]. The Band B receiver is shown in Fig. 6. Both mixer and frequency doubler use planar Schottky diodes from VDI [14].

The 310 GHz FSS has been measured independently with an *ABmm* Vector Network Analyser and QO bench system. The insertion losses are better than 1 dB in the band 290-305 GHz and the rejection factor is better than 30 dB in the frequency range 331-343 GHz. The performance of the SSB receiver featuring the band B receiver and the FSS described above is measured using a Y-factor measurement. The reflected sideband is loaded with a 300 K calibration target. A SSB receiver noise temperature of approximately 5000 K is obtained at an RF frequency of 300 GHz, and a DSB receiver noise temperature of approx. 2100 K without the FSS inserted in the QO path.

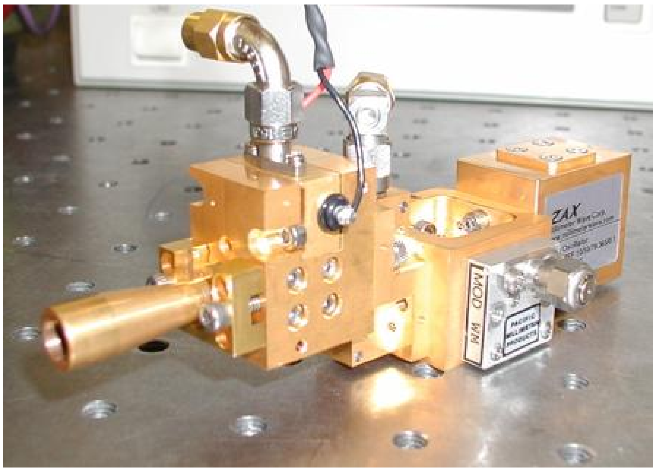

Fig.6. Photo of the MARSCHALS Band B receiver channel, featuring a 295-350 GHz DSB sub-harmonic mixer with integrated pre-amplifier (foreground), a 160-185 GHz frequency doubler (middle), a 20 dB cross-guide coupler and a Gunn diode oscillator from ZAX (background).

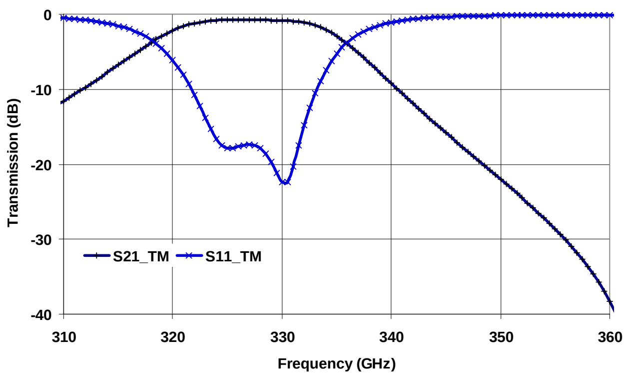

Fig.7. Simulated transmission and reflection coefficients of an FSS *VS* RF frequency based on the membrane technology developed at QUB, normalized by 6 GHz. (Courtesy: Queens University Belfast, Ireland).

A plot of the simulated transmission and reflection coefficients of an FSS based on the membrane technology developed at QUB that would be suitable for STEAM-R instrument is presented in Fig.7. It shows that, if one wants to use a single FSS to separate the LSB from the USB of an incoming RF signal before feeding two DSB mixers, the IF central frequency and bandwidth of both sidebands will determine the amount of rejection and QO losses that can be achieved. Furthermore, QO FSS are for the moment non-reconfigurable and have a fixed frequency response.

The reflected band shown in blue (S11_TM) in Fig.7 shows that the maximum rejection achievable is 18 dB and 10 dB for an IF bandwidth of 7 GHz to 10 GHz respectively. For an maximum image rejection of 10 and 18 dB in each sideband, the lower IF frequency should not be bellow 4 and 7 GHz respectively from the carrier.

In the SHIRM case, the rejection is much less sensitive to the IF frequency range and bandwidth, as the IF band can start as low as few MHz. The LO frequency can also be tuned into a specific bandwidth without, in principle, degrading the image rejection of the SHIRM. The IF bandwidth is however a trade-off between amplitude and phase imbalance of the IF hybrid in the band (the broader the band, the higher the risk of imbalances). In the light of the first results presented in this paper, a similar level of rejection between the SHIRM and the QO FSS is achieved.

Further measurements on the SHIRM are required to confirm these assumptions.

CONCLUSION

The first operation of an integrated 340 GHz Sub-Harmonic Image Rejection Mixer using planar Schottky diodes is presented. Best image rejection of 23.8 dB and SSB receiver noise temperature of 3300 K is reported. An image rejection between 7.6 dB and 23 dB is measured between 317.5 GHz and 362.5 GHz. The device demonstrates the suitability of this approach for future remote sensing instruments requiring high spectral resolution and high sideband separation in the millimetre and sub-millimetre wave domain. Further developments are envisaged to improve the integration of the SHIRM into linear arrays of receivers.

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