# Sub-millimeter Wave 183 GHz and 366 GHz MMIC Membrane Sub-harmonic Mixers

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*Abstract* — **The design, fabrication and testing of broadband fixed-tuned 183 GHz and 366 GHz sub-harmonic mixers is discussed. Two mixer circuits using planar Schottky diodes monolithically integrated with RF/LO and IF matching and filtering networks onto a 3.7 um thick GaAs membrane are presented. The mixers were designed and fabricated using a novel approach in post processing of commercial foundry wafers. The double sideband measurements at room temperature on the 183 GHz sub-harmonic mixer yielded conversion loss and noise temperature of 4.9 dB and 608 K, respectively. The measured double sideband conversion loss and noise temperature of the 366 GHz mixer were 6.9 dB and 1220 K, respectively. To the authors' knowledge these are the best published results for sub-harmonic MMIC membrane mixers at these frequencies.**

*Index Terms* — **Planar Schottky diodes, sub-harmonic mixer, submillimetre wave mixers, submillimetre wave membrane mixer, submillimetre wave receivers.**

## I. INTRODUCTION

There is a growing need for compact, reliable, high performance heterodyne receivers for millimetre and submillimetre applications such as airborne and space-based microwave sounding, and also ground-based radiometric applications such as imaging and security scanning. For cost, performance and repeatability reasons such applications require broadband, solid state integrated sub-harmonic mixers with high sensitivity at room temperatures.

In that context we present here a 183 GHz (SPM-05) and a 366 GHz (SPM-2.8) sub-harmonic mixer. The mixers were designed and fabricated using the commercially available UMS BES Schottky diode foundry process and specific post processing techniques developed by Tyndall National Institute. The mixers present stat-of-the art performance and offer broad instantaneous bandwidths suitable to accommodate most needs of submillimtre radiometric sensing as well as transmit-receive applications.

## II. DESIGN

The mixers were designed, assembled and tested at Farran Technology based on the E-plane block split of RF and LO waveguides – similar to the one described in [1]. Both RF and LO waveguides were perpendicular to the circuit channel which accommodated the MMIC membrane substrate. The mixers substrates utilise beam leads for mechanical support as well as for DC and RF grounding. The Schottky diodes were organized in anti-parallel configuration ensuring sub-harmonic mixing action with all associated benefits (e.g., lower required LO frequency and higher LO-RF isolation [2], [3]).

The wafer and calculated diodes parameters (obtained by extrapolation of foundry user manual parameters) used in the design are presented in Table 1:

TABLE I
WAFER AND DIODE PARAMETERS

| **Parameter** | **Description** | |
|---|---|---|
| Device | SPM-05 | SPM-2.8 |
| Si doping | 2e17 / $cm^3$ | |
| Epi layer thickness | 80 nm | |
| Junction size | 2 $um^2$ | 1 $um^2$ |
| Ideality factor n | 1.3 | |
| Saturation current $I_{sat}$ | 1.4e-14 A | 0.7e-14 A |
| Series resistance $R_s$ | 5.8 Ohm | 11.6 Ohm |
| Fringe field capacitance $C_{je}$ | 4.8 fF | 3 fF |
| Depletion capacitance $C_{jj0}$ | 0.61 fF | 0.31 fF |
| Membrane thickness | 3.7 um | |

For the best design accuracy a combination of full 3-D electromagnetic modeling (High Frequency Software Simulator - HFSS) with harmonic balance and linear analysis (Advanced Design System - ADS) was used. This typical CAD technique is described in details in [4]-[6] and will therefore not be discussed here. As well, the nonlinear Schottky diode model implemented in ADS used classical equations that are well described in available literature [7].

### A. The SPM-05 183 GHz Sub-harmonic Mixer Design

The 183 GHz sub-harmonic mixer was designed on a GaAs beam-leaded membrane substrate that is suspended in the circuit channel. The mixer is a straight-in-line design where DC and IF ground are provided by a narrow stub connected to one of the beam leads. The anti-parallel pair of Schottky diodes is positioned along the main axis of the channel. Parasitic capacitance reduction was achieved by etching the GaAs membrane around the anode fingers. A complete view

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of the full SPM-05 mixer model and its positioning within the waveguide and channel cavities is shown in Fig. 1:

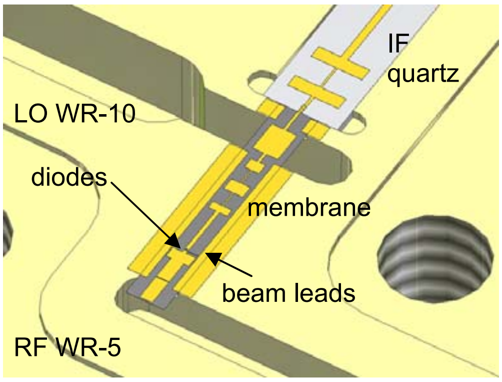

Fig. 1. Schematic bottom block view of the SPM-05 183 GHz sub-harmonic mixer.

The mixer uses a full height WR-5 RF waveguide and a reduced height WR-10 LO waveguide for membrane length reduction. The electrical grounding is achieved by suspending the membrane between the top and bottom metal blocks and pressing them together, thereby closing the waveguide and channel cavities. For an RF frequency of 183 GHz and an LO drive level of 5 mW the harmonic balance (HB) analysis for compromised performance between optimum noise temperature and conversion loss yielded the RF, LO and IF optimum impedances of $Z_{RF}$ = 28-j28 Ohm, $Z_{LO}$ = 53+j50 Ohm and $Z_{IF}$ = 100 Ohm, respectively. Based on these values all matching networks were synthesized using HFSS including all dielectric and conductive losses. The electromagnetic and HB synthesis provided a mixer with double sideband (DSB) noise temperature NT = 473 K and conversion loss CL = 4.8 dB for an IF frequency of 4 GHz.

### *B. The SPM-2.8 366 GHz Sub-harmonic Mixer Design*

The fixed-tuned sub-harmonic 366 GHz mixer was also designed using full integration on a 3.7 um GaAs suspended membrane and a strip line technology. The input RF (WR-2.8) and LO (WR-5) waveguides were kept at full heights for waveguide and channel simplicity.

The circuit was designed in an innovative topology with an IF filter integrated on the membrane and perpendicular to the RF-LO part of the mixer. This arrangement made possible by the design flexibility offered by GaAs membrane technology, not only reduces the overall length of the circuit but also improves significantly its mechanical robustness which eases the assembly process.

The Schottky diodes were arranged for anti-parallel configuration in a novel manner - unlike in all sub-harmonic mixer designs known to the authors [4]-[6] and [8]-[13], as they were positioned across the membrane and circuit channel. This structure not only benefits from permanent ground at all frequencies but also from the fact that with careful design both diodes can be perfectly balanced by adjusting the relative position of one junction in relation to the other across the channel (as shown in Fig. 4). This feature of the design is particularly interesting for high sensitivity sub-harmonic mixers at frequencies of 400 GHz and higher. The full SPM-2.8 mixer model is shown in Fig. 2:

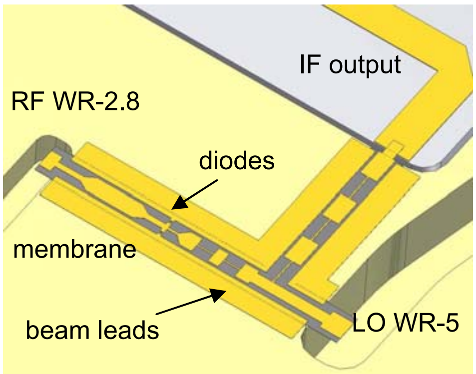

Fig. 2. Schematic bottom block view of the SPM-2.8 sub-harmonic mixer.

The mixer design also employed GaAs etching around the anode fingers, and also focused on a trade-off between minimum noise temperature and minimum conversion loss. For an RF frequency of 366 GHz and an LO drive level of 7 mW the HB analysis yielded the optimum impedances for RF, LO and IF networks of $Z_{RF}$ = 55 – j55 Ohm, $Z_{LO}$ = 20 + j19 Ohm and $Z_{IF}$ = 50 Ohm. The mixer model with all matching networks, including conductive and dielectric losses presented a DSB noise temperature NT = 775 K and a conversion loss CL = 6.6 dB at room temperature.

## III. FABRICATION

Submillimetre wave mixer circuits have commonly used planar diode chips bonded to thin (~100 um) quartz substrates. There is an obvious advantage for manufacturing and performance if the diode can be monolithically integrated with the substrate. However the substrate must be thinned to a point where parasitic electrical effects are negligible or manageable because a semiconducting substrate with undesirable high dielectric losses must be used for the diode fabrication. This was accomplished in this work by thinning the semiconductor substrate to a thickness of 3.7 um.

The mixers were fabricated using Schottky membrane technology as a post processing technique developed at Tyndall National Institute applied to part processed wafers from United Monolithic Semiconductor’s (UMS) BES-MMIC process. Post processing was used to fabricate the beamleads, probes, and transmission lines, before the wafers were thinned to form GaAs membranes.

The UMS Schottky diode uses implantation to isolate the anode junction which limits the operating frequency due to the high dielectric material (GaAs) under and around the anode finger connection to the anode. During the post processing, GaAs was removed from around the UMS finger structure effectively making an air bridged connection to the anode.

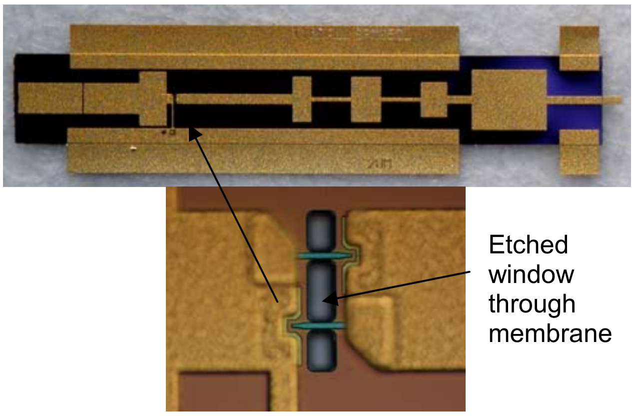

Fig. 3. Image of fabricated 183GHz mixer membrane and detail of diodes showing airbridged anode connection.

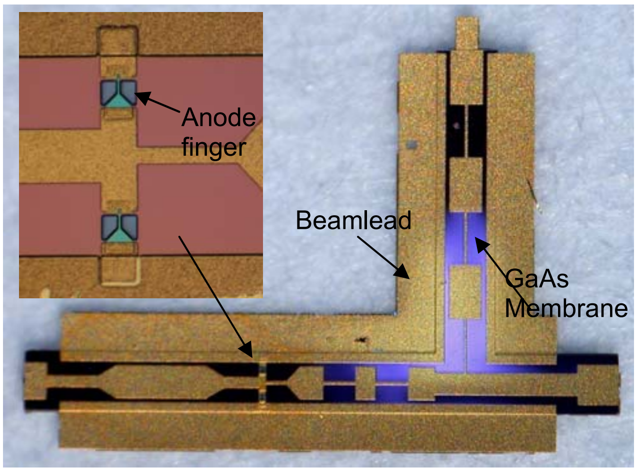

Fig. 4. Image of fabricated 366GHz mixer membrane with inset detail of diodes showing airbridged anode connection.

The membrane substrate was first defined and etched before seed metal for the beamleads, IF tab, and RF probe was deposited and then plated to the required thickness. The wafer was then thinned from the backside to a buried etch stop layer to release the membrane mixers. Images of the fabricated mixer membrane circuits are shown in Figs 3 & 4.

## IV. RESULTS

In order to drive the 183 GHz sub-harmonic mixer a back wave oscillator (BWO) was used, whereas a cascaded BWO with a power amplifier and a fixed-tuned doubler was used to provide the LO signal for the 366 GHz device. The power level of the LO sources was calibrated using a HP W8486A sensor (WR-10) and a PM2 Erickson power meter (WR-5).

To measure the noise temperature and the conversion loss of the mixers a standard Y factor was used. The method relies on presenting alternatively a room temperature and a black body cooled at liquid nitrogen temperature (~77 K). An IF amplifier was also used in the system contributing 2 dB of noise figure in a 500 MHz bandwidth centered at 4 GHz. The output signal was measured using a HP 8481D power sensor.

### *A. Performance of the 183 GHz Sub-harmonic Mixer*

The simulated and measured performance for 183 GHz sub-harmonic mixer is shown in Fig. 5:

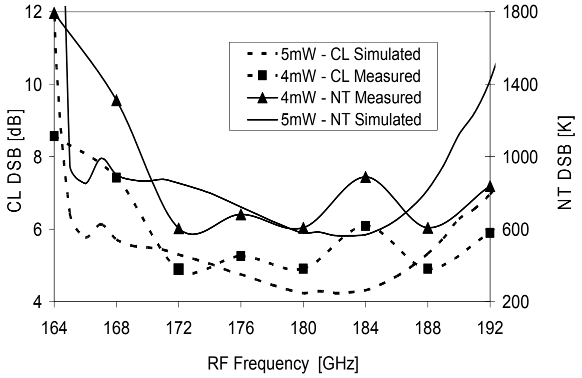

Fig. 5 Simulated and measured DSB performance of the 183 GHz sub-harmonic mixer – SPM-05.

At 180 GHz the mixer yielded minimum DSB conversion loss of 4.9 dB (4.1 dB simulated at 183 GHz) and noise temperature of 608 K (565 K simulated at 183 GHz) for an LO drive level of 4 mW (5 mW used in calculation). Over the 170 – 192 GHz RF band the mixer provides NT < 900 K and CL < 6 dB. The measurements are in a very good agreement with the simulations.

### *B. Performance of the 366 GHz Sub-harmonic Mixer*

The simulated and measured double sideband conversion loss and noise temperature characteristics of the mixer are shown in Fig. 6.

The mixer performs best with an LO drive level of 7.5 mW and at 364 GHz exhibits a DSB loss of 6.9 dB and a noise temperature of 1220 K. In a measurement range of 356 – 380 GHz the mixer provided CL < 8.3 dB and NT < 1560 K. The measured bandwidth was limited by the power available from the local oscillator and the mixer is believed to be performing well in the much wider range of 320 – 385 GHz with DSB CL < 9.5 dB and NT < 2000 K.

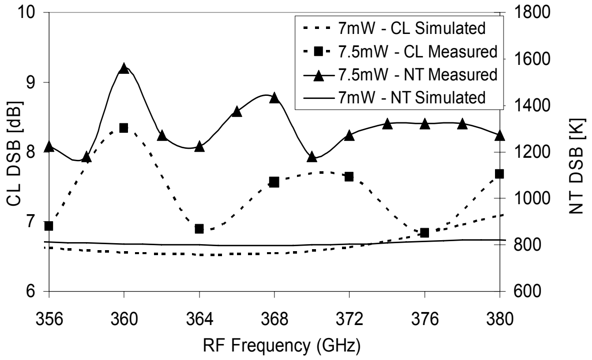

Fig.6 Simulated and measured performance of the 366 GHz sub-harmonic mixer – SPM-2.8.

### C. Results Comparison

Table 2 presents the best published results for DSB conversion loss and noise temperature for planar discrete and integrated diode sub-harmonic mixer designs:

TABLE II
STATE OF THE ART OF 183 AND 366 GHZ SUB-HARMONIC MIXERS

| $f_{RF}$ [GHz] | Technology | $NT_{DSB}$ [K] | $CL_{DSB}$ [dB] | Ref |
|---|---|---|---|---|
| 183 | discrete | 530 | 5.1 | [8] |
| 240 | int. on quartz | 510 | 5.4 | [9] |
| 175 | int. on GaAs | 2400 | 9.5 | [10] |
| 180 | int. on GaAs | 608 | 4.9 | this work |
| 330 | discrete | 700 | 6.3 | [11] |
| 380 | discrete | 850 | 8.5 | [12] |
| 390 | int. on quartz | 3667 | 10.9 | [13] |
| 366 | int. on GaAs | 1220 | 6.9 | this work |

To the authors knowledge the 183 GHz and 366 GHz sub-harmonic mixer presented exhibit state-of-the-art conversion loss and noise temperature performance for MMIC membrane devices at these frequencies.

## V. CONCLUSION

Monolithic 183 GHz and 366 GHz sub-harmonic mixers integrated on a GaAs membrane were successfully designed, fabricated and tested. The devices were fabricated using a commercial foundry process and novel post-processing techniques. The technique used in 366 GHz device could be a promising approach for sub-harmonic mixer design at higher frequencies where diode balancing is critical. Finally, both devices were shown to exhibit state-of-the-art performance and wide instantaneous bandwidths, making them suitable for use in high sensitivity radiometric and transmit/receive applications.

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