Numerical analysis of a 330 GHz sub-harmonic mixer with planar Schottky diodes, LERMA, Observatoire de Paris, France

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Abstract

A numerical analysis of different SHP mixers working at 330GHz is proposed. The possibility to model accurately the hot electron noise of Schottky diodes using Agilent ADS software suite has been investigated. Simulations are compared to measurements performed on a 330GHz SHP mixer built by ASTRIUM. A study of the sensitivity of two types of mixers to mounting tolerances is used to design a 330-345GHz fix-tuned split-waveguide-block SHP mixer. The circuit uses an anti-parallel pair of Schottky diodes fabricated by the University of Virginia and flip-chipped on a suspended micro-strip filter. Expected performances are mixer conversion losses of 7dB and DSB mixer noise temperature bellow 1000K with about 2.5mW of LO power.

Keywords: sub-harmonic mixer, planar Schottky diodes, hot electron noise.

1. INTRODUCTION

Space-borne millimeter-wave radiometers can provide unique insight in planetology science. Several missions in the near future will need instruments with high spectral resolution and high sensitivity to achieve a variety of scientific goals, ranging from the remote sensing of minor components in the Mars (MAMBO/Mars Premier) and Earth (ODIN, STEAM) atmosphere, to the understanding of physico-chemical processes in comets (MIRO/ ROSETTA). Radiometry at millimeter-wavelengths can also greatly contribute to better meteorological forecasting (MHS, SAPHIR/Mega Tropique). Only heterodyne detection techniques can provide both sensitivity and high resolution in this range of frequencies. Therefore, developments of innovative receiver components are essential.

Sub-harmonically pumped (SHP) mixers use a local oscillator signal (LO) corresponding to half of the RF signal frequency. This feature makes the SHP mixers very suitable for heterodyne observations at millimeter wavelengths. Actually, the main advantage of SHP mixers over fundamental mixers is that their local oscillator signal is much easier to generate with solid-state components, due to the reduced frequency. The other main advantage is that the injection of the RF and LO signals into the mixer is done through two different ports. Therefore, no diplexer at the RF port is needed, and the diode matching at the LO and RF frequencies can be optimized independently.

Many designs of millimeter SHP mixers have been proposed during the last decade for the applications mentioned above. The circuits use essentially planar devices fabricated either at the University of Virginia or at the Jet Propulsion Laboratory [1], [2], [3], [4]. Till the mid-90', the circuits were designed using both, custom-made harmonic-balanced codes, developed originally by Kerr [5] and Siegel [6], and scaled-models of the waveguide structure to respectively, calculate the impedances of the diodes and to measure the embedding impedances provided by the circuit. Tunable backshorts was often used to compensate the discrepancies between the design and the actual circuit.

For a decade, a number of commercial software have been developed to perform non-linear circuit simulations or to solve the electro-magnetic field inside the circuits. Thanks to a great increase in the performance of these codes, along with an even greater improvement of the computer power (memory more than speed), it is now possible to completely eliminate the expensive and time-consuming step, that consists to build first a scale model of the circuit before to fabricate it. Designing fix-tuned planar Schottky diode mixers [2] or monolithic frequency multipliers at millimeter frequencies [7], requires only the use of the codes mentioned above.

In that context, we propose to compare two different architectures of SHP mixers working in the 330GHz band by using a numerical model. The purpose of this study is to find a design which performances are as less sensitive as possible to fabrication tolerances. This study is also preliminary to the designing of future monolithic SHP mixers in this band of frequency. All the mixers considered in this paper use an anti-parallel pair of planar Schottky diodes SD1T7-D20 from the University of Virginia. They are waveguide SHP mixers which RF and IF filter are printed onto a quartz substrate. The planar diodes are flip-shipped on the filter strips. More details will be given in the following sections.

2. DIODE NOISE MODEL

The numerical model of the mixer is built in two parts. The first part describes the non-linear behavior of the Schottky barrier; the second part describes the linear embedding circuit.

Diode model, noise calculation: the diodes were modeled using Agilent ADS harmonic balanced code with its standard diode model. For each diode of the pair, the junction capacitance Cj0 (without its parasitic capacitance), the saturation current Is, the ideality factor η, the series resistance Rs, the anode diameter d, were given by the University of Virginia. Their values were directly implanted in the Agilent ADS standard model.
ADS can compute the thermal and shot noise of the mixer. However, Hegazi [8] and Crowe [3] showed that, with strong current densities inside the diodes at theses frequencies, an additional hot electron noise has to be added to the model. This noise, as well as the shot noise, exhibits cyclostationary properties, due its dependence on the currents generated by the LO. To determine the exact contribution of this noise source to the equivalent noise temperature of the mixer, the correlation between the large currents generated by the LO has to be known. Unfortunately, this correlation is calculated during the harmonic balanced simulation and is not an available result. Therefore, at this time, the contribution of the hot electron noise to the mixer noise temperature cannot be calculated using Agilent ADS software. Only custom codes can include such a noise model.

However, an upper limit of this contribution can be found by assuming that the large currents created by the LO are uncorrelated. In that case, these currents generate independent noise at the IF output port. To further calculate this upper limit, we made the assumption that the mean-square voltage noise source equivalent to the contribution of the hot electron noise, is proportional to the sum of the square of the effective currents of the harmonics of the LO signal. These currents can be retrieved from the harmonic balance simulation result given by ADS. In the specific case of an SHP mixer using few milliwatts of LO power, we found that this sum can be reduced to only three terms. Unfortunately, since these currents cannot be used to set any circuit parameter *during* the simulation, no model of hot electron noise can be implanted directly in ADS. It is necessary to record first the currents given by a primary simulation that does not include any noise model (or only the thermal and shot noise), and then to use them in a secondary simulation that fixes all the circuit parameters but that includes all the noise sources.

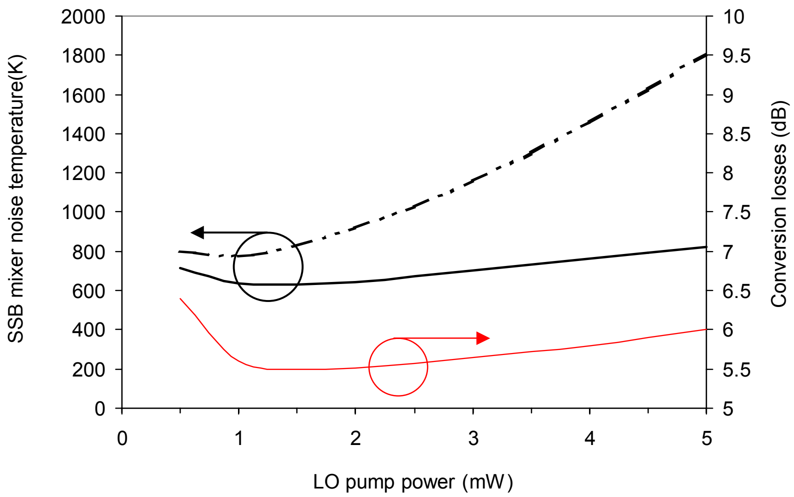

Fig.1: Equivalent noise temperature and conversion losses of an ideal mixer using a pair of Schottky diodes from UVa. Two noise models are considered: including shot and thermal noise only (upper full line), with shot, thermal and additional noise source equivalent to the upper limit of the hot electron noise (upper dashed line). Diode parameters for UVa SD1T7-D20 planar diode as followed: Cj0=1.3fF (no parasitic capacitance is included), Is=2E-16A, η=1.3, Rs=15Ω, d=1µm. Simulation parameters: F_{LO}=167GHz, F_{RF}=330GHz, F_{IF}=4GHz, Z_{IF}=150Ω.

Fig.1 shows the performances of an ideal SHP mixer using SD1T7-D20 diodes. Two noise models are considered: one including shot and thermal noises only, the other with shot, thermal and an additional noise source equivalent to the upper limit of the hot electron noise as described previously.

The graph clearly suggests that hot electron noise could be preeminent when the LO power coupled to the pair of diodes is in the range of 4 to 5 milliwatts. Thus, to optimize the mixer noise temperature, one has to keep the current through the diodes as low as possible, i.e. the LO power as low as possible, in the range of 1 to 1.5mW for this type of device.

Further investigation will focus in comparing the hot electron noise calculated rigorously using a custom harmonic balanced code with the model proposed above. The intent is to provide a reliable estimate that can be obtained easily with convenient commercial codes.

3. MIXER MODEL

To complete the mixer model, S-parameters of the passive elements used to match the diodes impedances are needed. These S-parameters are calculated with 3D electromagnetic-field solvers that use either the FDTD method or the Finite Element method. The equivalent model of the circuit is classically implanted in a non-linear ADS bench.

Simulation of the performances of a 330 GHz SHP mixer built by ASTRIUM: as experimental data were available, we took the opportunity to validate our numerical model by comparing them to simulations. This mixer is based on a scaled model of a 190 GHz SHP mixer built for the Microwave Humidity Sounder instrument. Fig.2 shows a schematic of the 330GHz SHP mixer. The anti-parallel pair of planar Schottky diodes are mounted on a 50µm-thick quartz substrate and located inside the circular RF waveguide. The circuit is grounded to the mixer block by a 100µm-wide gold bonding ribbon that is used as an impedance matching element at RF and LO frequencies. In addition to the main tunable backshort in the LO waveguide, an E-plane tuner (not shown in Fig.2) is added. Only one tunable backshort is used in the circular RF waveguide.

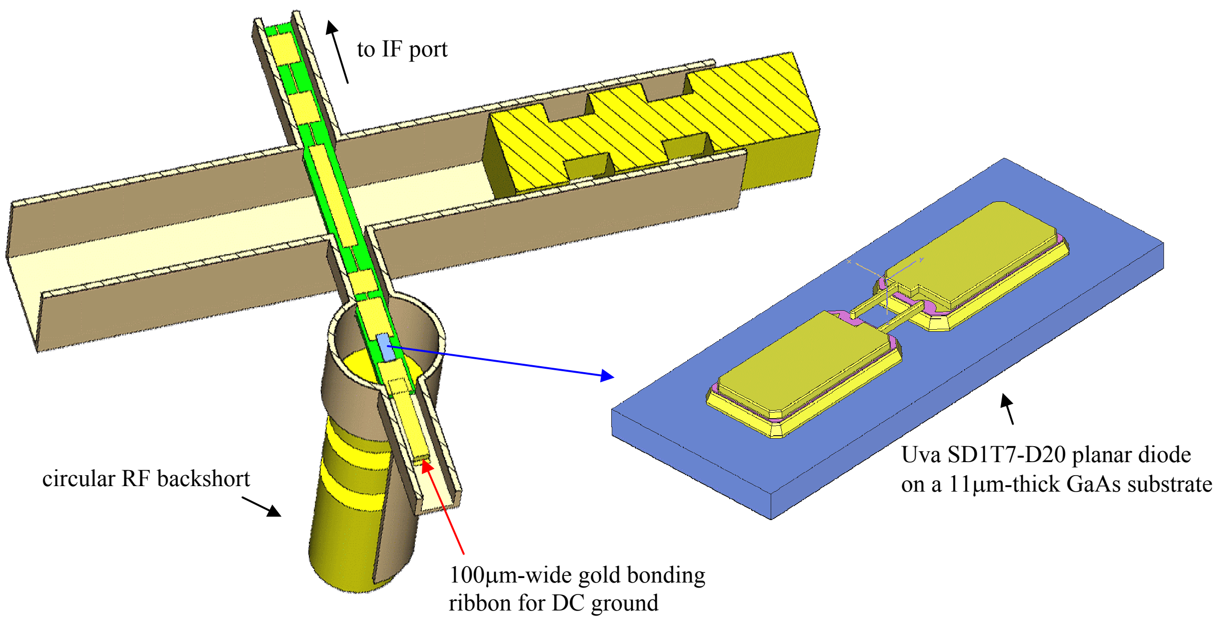

Fig.2 : Schematic of the 330GHz SHP mixer designed by ASTRIUM with detail of UVa SD1T7-D20 planar diode.

The 3D numerical model reproduces the details of the mixer with an accuracy of about 3-to-5µm. However, the backshorts were simulated using a perfect ground in series with a resistance to take into account the losses (0.2dB estimated for each LO backshort and 0.5dB for the RF backshort).

Fig.3 compares measured and simulated DSB noise temperature of a 330GHz receiver using that mixer. To calculate the DSB receiver noise temperature from the simulated noise temperature of the SHP mixer, quasi-optical losses of 0.2dB and LNA Noise Figure of 0.9dB have been assumed. A relatively good agreement between the simulations and the measurements has been found. We also find that one of the main behavioral characteristics of the mixer has been well reproduced by the model: the optimum LO power that varies within frequency is the same for both simulations and measurements.

Additional simulations show that the performances of the SHP mixer designed by ASTRIUM are sensitive to the positioning of the diode inside the RF waveguide as well as the thickness of the silver-epoxy glue used to connect the diode to the circuit. Although these parameters were carefully measured, some discrepancies between the actual values and the parameters set in the numerical model could partly explain the differences found at 329GHz.

In addition, some parameters like the mismatch at the IF port, the quasi-optical losses and the back-short losses as well as the exact position of the grounding of the bonding ribbon, are not known with accuracy. We have to point out that no parameter has been tuned to retrofit the measurements.

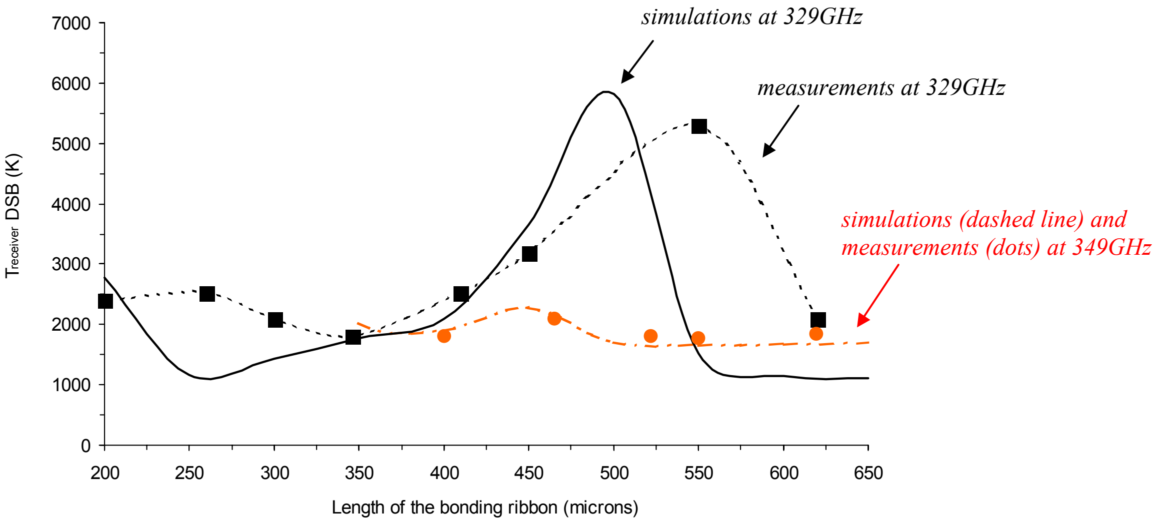

Fig.3 : Comparison between the simulations and measurements of a 330GHz receiver with a SHP mixer designed by ASTRIUM, using a UVa SD1T7-D20 planar diode. IF frequency is 1GHz. Estimated quasi-optical losses: 0.2dB, LNA Noise Figure: 0.9dB. The simulations are performed with shot, thermal and an additional noise source equivalent to the upper limit of the hot electron noise.

4. DESIGN OF A FIX-TUNED MIXER

We intent to design a 330GHz fix-tuned SHP mixer that is as insensitive as possible to fabrication and mounting tolerances. We tried to improve the performances of the SHP mixer described previously and to decrease its sensitivity to fabrication and mounting tolerances. The tunable backshorts have been removed. RF and IF filters have been re-optimized to get the best performances in the 330-345GHz RF band independently of the thickness of the silver-epoxy glue used to mount the diodes. Our simulations showed that if the mixer was optimized to be insensitive to other tolerances at the same time, its global performances were degraded. Fig.5a illustrates that behavior. This mixer requires a minimum of 5mW of LO power. Expected conversion losses are 7dB to 7.5dB giving a DSB receiver noise temperature of 1000K (hot electron noise not taken into account).

Another SHP mixer derived from the mixer proposed by Hesler in [2] was also designed. Its schematic is shown in Fig.4. The mixer is in a split-waveguide-block configuration. The anti-parallel pair of Schottky diodes is mounted on a 50µm-thick quartz substrate. The whole circuit is flip-chipped and suspended inside the channel. This architecture allows a precise grounding of the circuit by soldering the RF antenna strip end to the block. The RF and LO signals are coupled to the circuit by two E-probes crossing respectively the reduced-height RF and LO waveguides. One step in the RF waveguide and several steps in the LO waveguides are used to match the diodes. The design has been optimized to be fairly insensitive to slight shifts of the quartz substrate, as well as variations of the thickness of the silver-epoxy glue.

This mixer uses a minimum LO power of 2.5mW. Expected conversion losses are 6.5dB to 7dB giving a DSB receiver noise temperature of 850K (hot electron noise not taken into account).

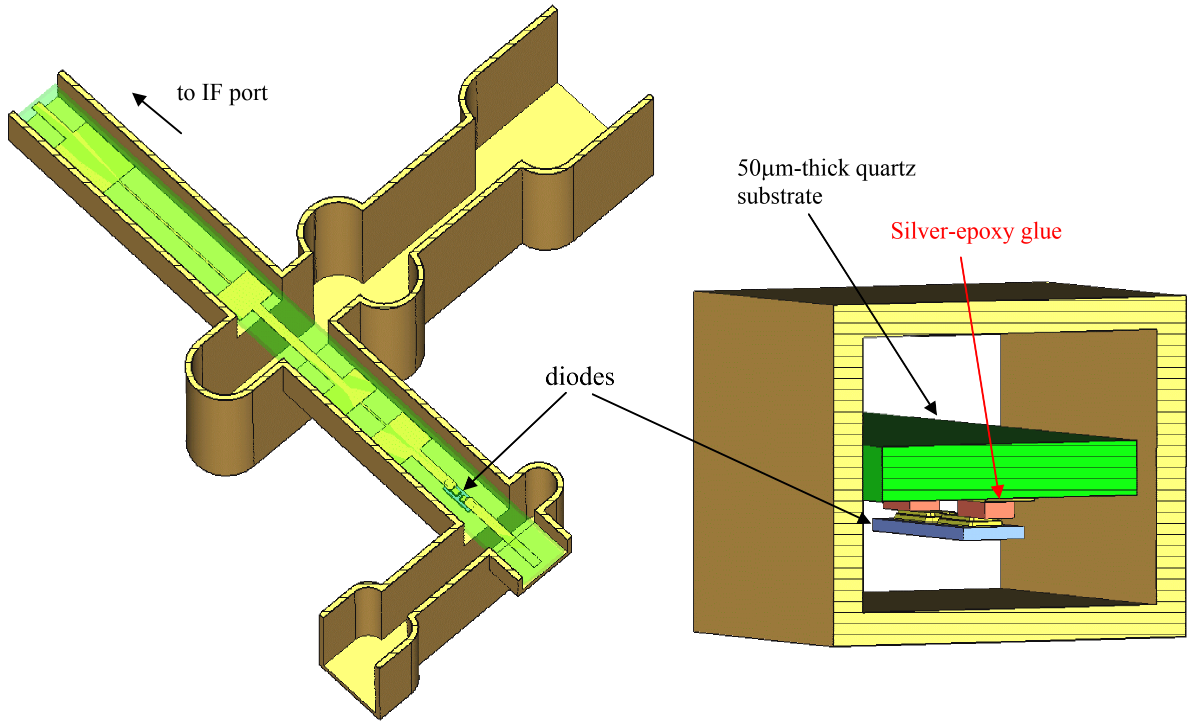

Fig. 4 : Fix-tuned SHP mixer with flipped and suspended quartz substrate derived from a mixer designed by Hesler.

Sensitivity to mounting tolerances : we focus on two parameters: the thickness of the silver-epoxy glue used to connect the diode to the circuit and the positioning of the quartz substrate. Fig. 5a and 5b. show the impact of variations of these parameters on the DSB receiver noise temperature of the mixers described above.

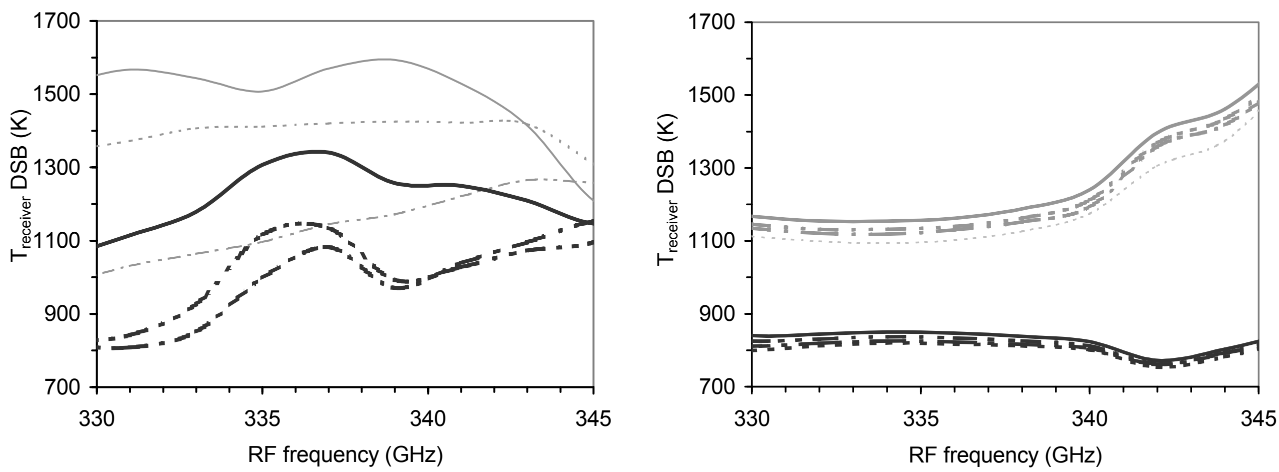

Fig. 5a (left) and Fig. 5b (right) : calculated DSB receiver noise temperatures of the fix-tuned SHP mixer derived from the design of ASTRIUM (left) and derived from Hesler's design (right). Only thermal and shot noises are modeled. In both cases, the curves in black are related to the nominal position of the circuit, with the thickness of the silver-epoxy glue ranging from 8µm to 18µm. The curves in grey are related to a shift of the position of the circuit of 50µm towards the IF port, with the thickness of the silver-epoxy glue ranging from 8µm to 18µm. For each simulation, the LO power was adjusted to get the best performances (5mW for the first mixer, 2.5 to 5mW for the second mixer).

The curves indicate that the first design (left curves - the diodes are located in the middle of the RF waveguide) seems to be less robust to mounting tolerances than the second one (left curves - the diodes are located inside the filter channel). Depending on the type of design, the thickness of the silver-epoxy glue used to connect the diodes to the circuit is or is not a critical parameter. According to these results, we believed that non-monolithic fix-tuned SHP mixers should be designed with the diodes located inside the filter channel, to reduce the impact of some critical mounting tolerances. The fabrication of the mixer presented in Fig. 4 is on its way.

5. CONCLUSION

The design of a robust fix-tuned SHP mixer working in the frequency range of 330-345GHz with minimum LO power requirements has been presented. The numerical model has been validated by measurements performed on a prototype. At this time, we found find no way to accurately model the hot electron noise of Schottky diodes using Agilent ADS software suite. Only an estimated upper limit of this noise could be used to drive the optimization of the mixers. A fix-tuned SHP mixer will be built according to the results of this study. Expected performances are mixer conversion losses of 7dB and DSB mixer noise temperature bellow 1000K with about 2.5mW of LO power.

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