Local oscillator requirements and noise performance of a cryogenic 360 GHz Schottky diode subharmonic mixer

D. Pardo[1*], H. Wang[1], B. Ellison[1], P. Huggard[1], B. Alderman[1], and J. Grajal[2]
[1]*STFC-Rutherford Appleton Laboratory, OX11 0QX, Oxfordshire, UK*
[2]*Universidad Politécnica de Madrid, E.T.S.I. Telecomunicación, 28040, Madrid, Spain*
*Contact: diego.pardo@stfc.ac.uk

Abstract— Improving the cryogenic performance of subharmonic Schottky mixers in terms of minimum noise and LO power is of high relevance for a large number of space missions. In this work we carry out a theoretical and experimental analysis of a 360 GHz subharmonic mixer at 77 K in order to improve our understanding of cryogenic mixers and provide a procedure to reduce the LO power required by these receivers. By using a physics based model of the diode it will be shown that the increase on the LO power reported in the literature for cryogenic subharmonic mixers is related to the increase of the mismatch of the LO source, and that this effect can be taken into account in the design stage by using proper physics based diode models.

I. INTRODUCTION

The majority of heterodyne receivers used in spaceborne Earth observation and planetary science missions use GaAs Schottky barrier diodes as the first frequency down-conversion (mixer) element. This is primarily due to the maturity of the technology, its ability to be configured as different mixer topologies, e.g. as multiple diode subharmonic mixers, and to operate at both room and cryogenic temperatures. A brief review of related planned European space missions reveals the continued importance of this technology with mission examples including: MicroWave Sounder (MWS), Microwave Imager (MWI) and Ice Cloud Imager (ICI) on-board the European Space Agency's (ESA) MetOp-SG satellites with heterodyne receivers operating at frequencies between 183 GHz and 664 GHz [1]; the Submillimetre Wave Instrument (SWI) of the Jupiter ICy Moons Explorer (JUICE) mission of the ESA consisting of two heterodyne receivers working at approximately 600 GHz and 1.2 THz [2]; and the LOw Cost Upper atmosphere Sounder (LOCUS) concept mission [3] that aims to use Schottkky mixers in four discrete frequency bands of 0.8 THz, 1.15THz, 3.5 THz and 4.7 THz.

In the above examples, Schottky diode receivers operate within either a room or cryogenic temperature environment. Under cryogenic conditions, a well-known enhancement in receiver system sensitivity is gained through a corresponding reduction in mixer and intermediate frequency amplifier noise, with the former the dominating contributor. Less well understood is the change in local oscillator (LO) power required to pump the cryogenic mixer, particularly with respect to a subharmonic (SHP) mixer configuration which can be difficult to dc bias for optimum performance. Results from the former SWI mission [2], for instance, indicated a reduction by nearly a factor 2 in receiver noise temperature at 560 GHz when cooled to 140 K, but at the expense of a doubling in LO power. Similar performance for the noise and the LO power of a subharmonic 1.46 THz Schottky receiver have been reported by VDI when the receiver is cooled to 75 K [4]. Additionally, modern mixer design techniques have obviated the need for mechanical backshort tuning leading to compact device structures exhibiting excellent room temperature performance, but that lack a means of optimisation when cooled. Thus, despite the improvement in the noise temperature achieved via cryogenic receiver operation, the correlated increase in LO power is a significant disadvantage and has impact upon the space payload design and can ultimately limit science return through constrained operational frequency, e.g. tuneable bandwidth, and a restriction in the number of reception channels. It is therefore essential to understand the theoretical attributes of the mixer diode, including circuit requirements, in terms of achieving optimum LO power and noise in a cryogenic context. Doing so allows the development of device design models that are optimised for low temperature performance.

In this work, we report on a theoretical analysis and experimental investigation of the performance of a 360 GHz Schottky diode subharmonic mixer operated at an ambient temperature of ~77K. By using a physics-based drift diffusion (DD) model of the diode coupled to a multi-tone harmonic balance (HB) circuit simulator [5], it will be shown that it is possible to gain a significant improvement in the LO power required to achieve optimum noise performance. We compare results obtained for the same device at both low and room temperatures, and also with results obtained via other researchers using similar mixer configurations.

II. CRYOGENIC TESTS OF SCHOTTKY DIODES UNDER DC CONDITIONS

GaAs Schottky diodes with anode diameter 5.62 µm and 0.95 µm fabricated by *Teratech Components Ltd* were used in this test. On block current versus voltage measurements of the diodes for temperatures between 77 K and 295 K (IVT) were carried out. The temperature of the diode block was controlled with a liquid nitrogen cryostat. Fig. 1 shows measured results for the diodes with smaller anode diameter.

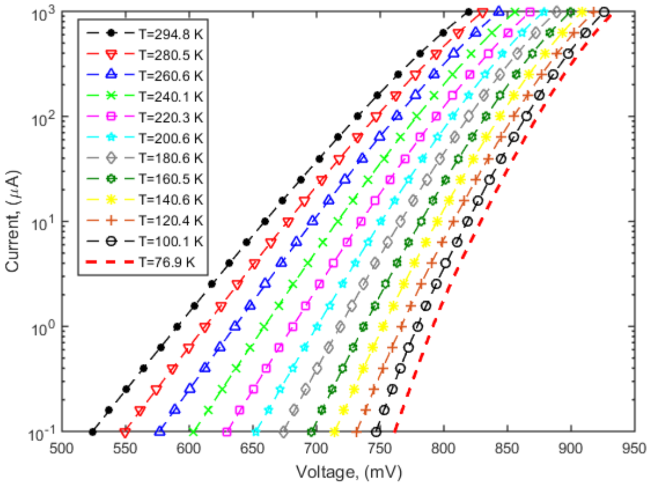

Fig. 1 Current versus voltage measurements as a function of the temperature for diodes with anode diameter 0.95 µm.

From the IVT measurements, the series resistance of the diodes was extracted using the technique described in [6], see Fig. 3 were a comparison with DD simulation results is included. For the diodes with anode diameter 5.62 µm, the series resistance decreases when the temperatures decreases, as expected from the DD simulations. Such a decrease is related with the increase of the electron mobility with the decrease of the temperature. However, the measurements for the diodes with anode diameter 0.95 µm show an increase of the series resistance related to self-heating effects in the diode. Such effects have a significant impact on submicron diodes as described in [7].

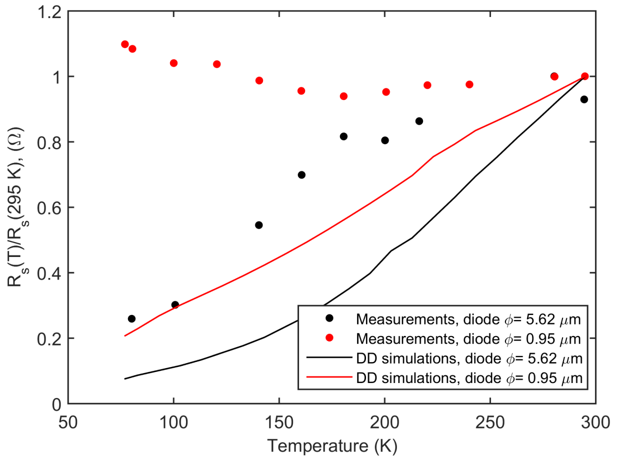

Fig. 2 Series resistance normalized by the values at 295 K as a function of the temperature for the diodes with anode diameter 5.62 µm and 0.95 µm.

The temperature dependence of the ideality factor and fundamental barrier of these diodes were also evaluated by fitting to the standard exponential performance of thermionic emission, as is shown in Figs. 3 and 4. The ideality factor increases as the temperature decreases due to the increase of the thermionic field emission current component [8]. The differences between the measurements and the prediction of the thermionic emission current component are generally attributed to density of states on the surface of the semiconductor, crystal defects, surface roughness or the presence of insulating interfacial layers.

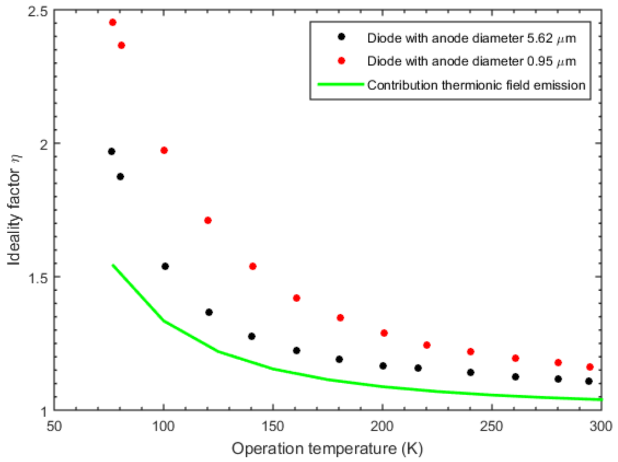

Fig. 3 Ideality factor as a function of the temperature for the Schottky diodes with anode diameter 5.62 µm and 0.95 µm.

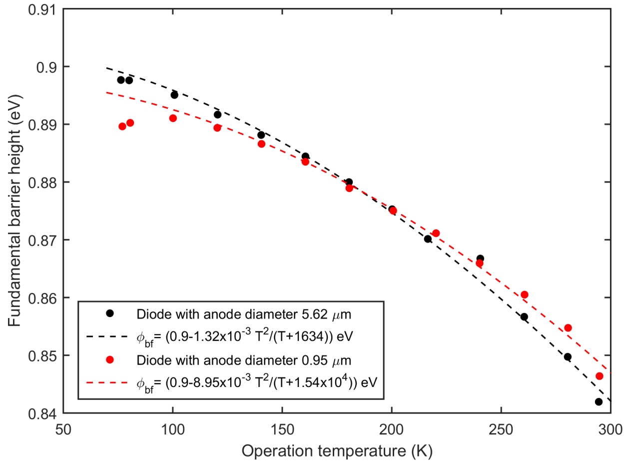

Fig. 4 Fundamental barrier height as a function of the temperature for the Schottky diodes with anode diameter 5.62 µm and 0.95 µm.

The fundamental barrier height is defined by the following equation [9]:

$$\emptyset_{bf} = \eta\emptyset_{b0} + (\eta - 1)\frac{k_B T}{q} ln\left(\frac{N_c}{N_d}\right) \tag{1}$$

where η is the ideality factor, $\emptyset_{b0}$ is zero bias barrier height, N_c is the effective density of states in the conduction band, N_d is the doping density, and k_B is Boltzmann's constant. The measured dependence of $\emptyset_{bf}$ on the temperature, see Fig. 4, is in agreement with the assumption that it is entirely due to the change of the energy gap of the semiconductor (E_g) with the temperature as suggested by some authors [10]. According to [10], the dependence of E_g on the temperature for GaAs is given by:

$$E_g(T) = \alpha - \beta T^2/(T+\gamma) \qquad (2)$$

with α=1.522, β= 5.8x10^{-4}, and γ=300.

III. ANALYSIS OF A 360 GHZ SUBHARMONIC MIXER AT CRYOGENIC TEMPERATURES

As was mentioned in the introduction, results published by different groups [2, 4] have shown that the operation of subharmonic Schottky mixers without tuning elements at cryogenic temperatures is accompanied by a reduction of the noise temperature but at the cost of considerably higher levels of LO power compared with room temperature operation. In this section, we present experimental and theoretical analyses of a 360 GHz subharmonic mixer in order to improve our understanding of the cryogenic performance of Schottky receivers. The subharmonic mixer used in the tests was designed to operate at room temperature, and it uses an antiparallel diode pair of anode diameter 0.95 µm, whose experimental characterization under dc conditions was presented in the previous section.

The two experimental setups in Fig. 5 have been analysed for the 360 GHz SHP mixer. In setup 1, the Schottky based frequency doubler pumping the mixer is outside the cryostat and, hence it is not cooled at 77 K. In the setup 2, the doubler is inside the cryostat and it is cooled with the mixer. The analysis of these setup will provide information about the coupling of the LO power to the mixer at 77 K.

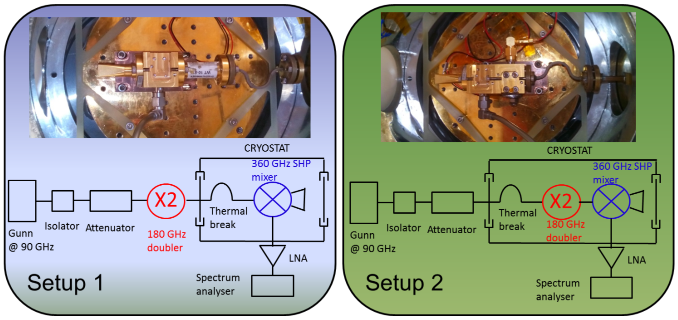

Fig. 5 Sketches of the experimental setups analysed for the 360 GHz SHP mixer. Pictures of the receiver in the cryostat for each setup are also included.

A. *Setup 1: doubler outside the cryostat*

Figs. 6 and 7 show the DSB mixer noise temperature and conversion loss measured for the 360 GHz SHP mixer in setup 1 at 295 K and 77 K. When the mixer is cooled at 77 K, there is a reduction of the noise temperature by nearly a factor 2 and an improvement of 1 dB in the conversion losses. Contrary to published results for SHP mixers [2, 4], where the LO power required to achieved minimum noise increases when the mixer is cooled, these figures indicate that it is practically the same at 295 K and 77 K.

The DDHB simulations of the conversion losses of the mixer are included in Fig. 7, showing a good agreement with the measurements at both operation temperatures. The DD model takes into account the change of the diode properties when it is cooled, i.e. the reduction of the series resistance, increase of the ideality factor, increase of the fundamental barrier height, and a reduction of the zero-bias junction capacitance associated to the increase of the built-in potential , see section II. Despite the variation of those parameters for the cryogenic mixer diodes, the simulations indicate that there is not a significant change of the coupling of the LO power to the diode pair when operated at 77 K.

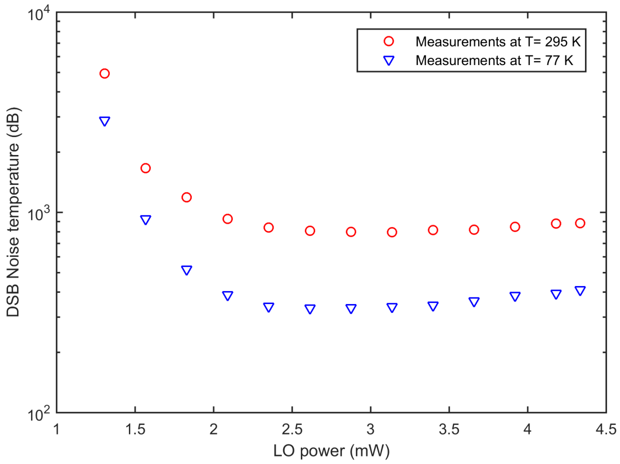

Fig. 6 Measured DSB equivalent input noise temperature of the 360 GHz SHP mixer in setup 1 operating at 295 K and 77 K.

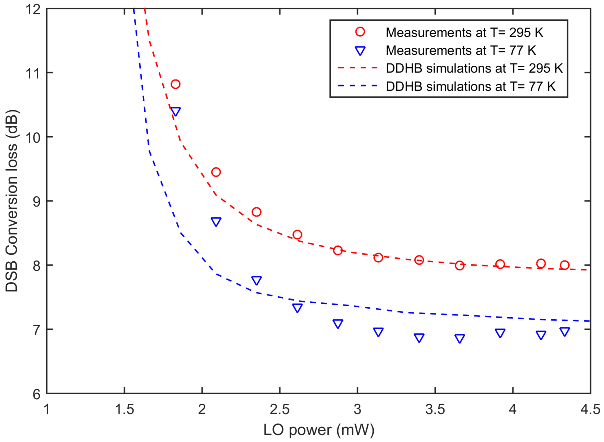

Fig. 7 Measured DSB conversion loss of the 360 GHz SHP mixer in setup 1 operating at 295 K and 77 K. DDHB simulation results are also shown.

A. *Setup 2: doubler inside the cryostat*

The measured results of the 360 GHz mixer in the setup 2 at 295 K and 77 K are shown in Figs. 8 and 9. When the setup 2 is cooled at 77 K, there is an improvement on the noise temperature and conversion loss similar to the improvement observed in setup 1. However, in this case the LO power required to achieved the minimum noise increases by around 0.5 mW when the receiver is cooled at 77 K.

The conversion losses of the mixer were simulated with the DDHB tool, see Fig. 9. A good agreement with measurements is observed at room temperature, but not at 77 K. In this simulations, the LO circuit impedance at 295 K was also used in the simulations at 77 K (blue dashed line in Fig. 9). In order to reproduce the measurements at 77 K in setup 2, the LO circuit impedance has to be increased by *j*35 Ω (black solid line in Fig. 9). This result indicates that there is a degradation of the coupling of the LO power to the mixer when the LO source is cooled, which causes an increase of the LO power required to achieved minimum noise.

Accounting for this degradation of the LO power coupling at cryogenic temperatures in the design stage will avoid the increase of the LO power detected in this analysis.

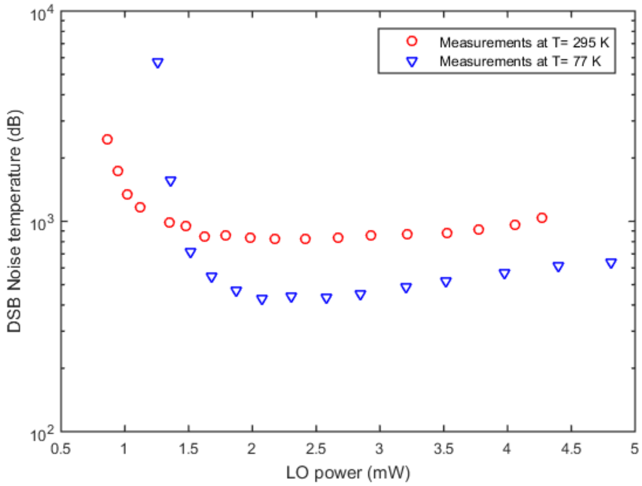

Fig. 8 Measured DSB equivalent input noise temperature of the 360 GHz SHP mixer in setup 2 operating at 295 K and 77 K.

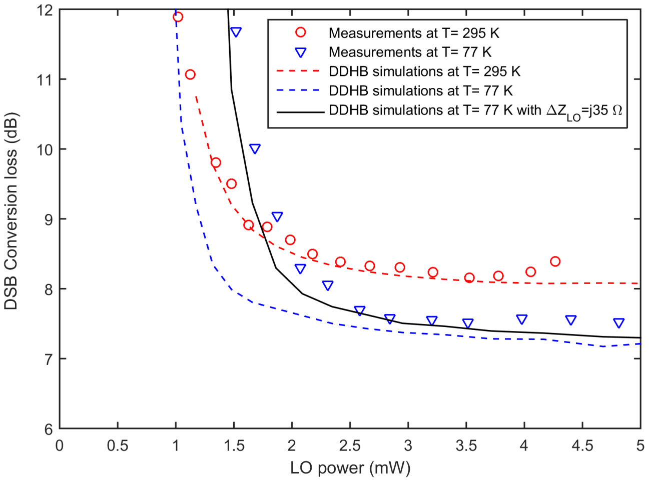

Fig. 9 Measured DSB conversion loss of the 360 GHz SHP mixer in setup 2 operating at 295 K and 77 K. DDHB simulation results are also shown.

IV. CONCLUSION

The cryogenic performance of a 360 GHz subharmonic Schottky mixer has been analysed experimentally and theoretically by means of a physics based drift diffusion diode model. Measurements of the receiver show an improvement of the conversion loss by 1 dB and the noise temperature by a factor 2 when the receiver is cooled at 77 K. The experimental tests carried out have shown an increase of the LO power required to reach minimum noise when the LO source also operates cryogenically, in agreement with published results. The simulation of the experimental setup with a DD model has shown that such increase of the LO power is due to a degradation of the coupling of the LO power to the mixer diode when the LO source operates cryogenically. Accounting for this LO mismatch during the design stage with an accurate diode model like the DD model used in this work, will lead to cryogenic receivers with improved LO power requirements.

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