Characterising the Effective Temperature of Hybrid Tunnel Junctions in THz SIS mixers

A. Traini, B-.K. Tan, J. Garrett, A. Khudchenko, R. Hesper, A. M. Baryshev, P. N. Dmitriev, V. P. Koshelets and G. Yassin

***Abstract*—In this paper, we present a method to measure the effective physical temperature of the tunnel junction in a terahertz superconductor-insulator-superconductor (SIS) mixer when illuminated with a strong local oscillator (LO) power that results in local hot spot around the tunnel junction. We observed that the gap voltage of the pumped current-voltage (IV) curve is suppressed when the LO pumping level is increased, indicating that the junction physical temperature is increased beyond the mixer block temperature. We quantified this extra heating effect by recovering the effective junction temperature through comparing the gap voltage of the pumped IV curves measured at a fixed block temperature, with the unpumped IV curve measured at varying block temperatures. We found that the heat trapped in the tunnel junction can be as high as 1.7 K when the mixer stabilised at 3.3 K is pumped at only 21% of the gap current.**

***Index Terms*—Terahertz SIS mixers, tunnel junctions, local oscillator heating effect.**

I. Introduction

SINCE the deployment of current Atacama Large Millimetre/sub-millimetre Array (ALMA), the Herschel Space Telescope, and the Stratospheric Observatory for Infrared Astronomy (SOFIA), the development of the next generation millimetre (mm) and sub-mm telescopes are now focusing on closing the 1–2 THz frequency gap. Observations at these frequency ranges are important for a wide range of scientific cases, including stellar formation at intermediate redshift universe and the Cosmic Infrared Background, where a host of spectral lines such as CO, NH^+ and other organic molecules can be detected [1]. Ground based observation in this frequency range is permitted through atmospheric transmission windows centred around 1.0, 1.3, and 1.5 THz [2]. To cover frequencies beyond these atmospheric windows, observation would need to be performed with high altitude or space observatories above the atmosphere.

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Although it is possible to operate a heterodyne receiver using the hot electron bolometers (HEBs) in this frequency range, their deployment is unfavourable due to the relatively narrow intermediate frequency (IF) bandwidth. Superconductor-insulator-superconductor (SIS) mixers, on the other hands, can operate with much wider IF bandwidth, but have yet to demonstrate their feasibility above 1 THz. This is because of the limitation imposed by the commonly used niobium (Nb) technology. The performance of Nb tunnel junction tends to deteriorate when operating close to twice its gap frequency, around 1.3 THz. Furthermore, Nb based transmission line required to form the superconducting mixer circuit incur very high resistive losses above 0.7 THz.

In order to improve the sensitivity of SIS devices and extend the frequency coverage above 1.3 THz, Nb needs to be replaced with higher gap superconductors such as niobium nitride (NbN) or niobium titanium nitride (NbTiN). However, it has been shown that high quality full NbN or NbTiN tunnel junctions are difficult to fabricate. One solution is therefore to replace one of the Nb electrode with either NbN or NbTiN, forming a hybrid junction. However, these hybrid junctions working in conjunction with higher gap superconducting transmission lines could suffer from localised heating effect, due to quasiparticles trapping in the low gap superconductor sandwiched between high gap superconducting materials. This effect can be observed experimentally as shown in Fig. 1, where the superconducting gap voltage of the device is reduced notably when the mixer is injected with strong local oscillator (LO) power. This problem of heat trap in a tunnel junction has already been investigated theoretically [3], [4], [5], [6]. In this paper, we present an alternative method for measuring the effective temperature of the junction using only experimental data.

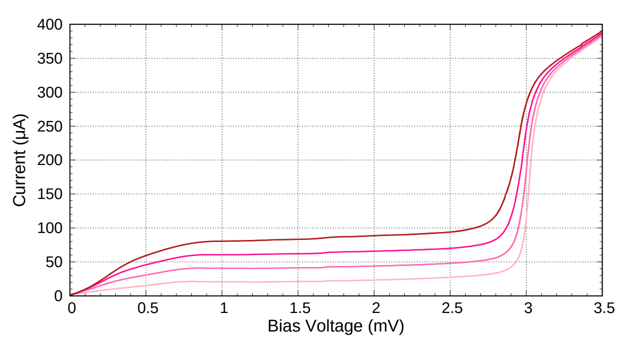

Fig. 1. Reduction of the gap voltage when the mixer, stabilised at a constant block temperature of 4 K, is injected with strong LO power.

II. Experimental Setup & Measurement Results

To investigate the amount of heat trapped in the tunnel junction when illuminated with strong LO power, we compare the gap voltage of a series of pumped current-voltage (IV) curves at varying pump levels and fixed mixer block temperature, with the unpumped IV curves at varying block temperature, since increasing the block temperature has the same effect of suppressing the gap voltage. The SIS mixer used in this experiment is a CHAMP+ (The Carbon Heterodyne Array of the MPIfR, Max Planck Institute for Radio Astronomy) mixer comprising niobium/aluminium-nitride/niobium-nitride (Nb/AlN/NbN) junctions deposited on NbTiN ground plane with aluminium (Al) as the top wiring layer [7].

The mixer was tested in the frequency range of 780–950 GHz, cooled with a pulsed-tube cooler cryostat, with all the optical components such as the beam splitter and the focusing mirrors mounted inside the cryostat to avoid the effect of water absorption [8]. The hot and cold loads required for Y-factor noise temperature measurements were also located inside the cryostat, with the respective physical temperature of 300 K and 4 K. The cryostat is also equipped with four temperature probes that were attached to the internal cold blackbody source, the mixer block, the cold plate and the second stage shield respectively. The cold plate and the second stage were further installed with resistors for raising the bath temperature above its minimum value. The current passing through the resistors is controlled by a proportional integral derivative (PID) controller loop made by Lake Shore®, to stabilise the mixer block temperature to a desired value, with accuracy of the order of mK.

Fig. 2 shows how we infer the effective temperature of the tunnel junctions. In this example, we first measured a pumped IV curve with the block temperature $T_{blk} = 4.0\,\mathrm{K}$, when illuminating with the LO set at at 831 GHz. We then measure a series of unpumped IV curves measured at varying T_{blk} =4.0–5.4 K, and look for the unpumped IV curve that have the same gap voltage as the pumped IV curve. As can be seen from Fig. 2, it is clear that the gap voltage of the measured pumped curve can only be matched with the unpumped curve where the block temperature is stabilised at 4.6 K. This indicates that there is an extra 0.6 K of heat trapped in the tunnel junction due to the LO.

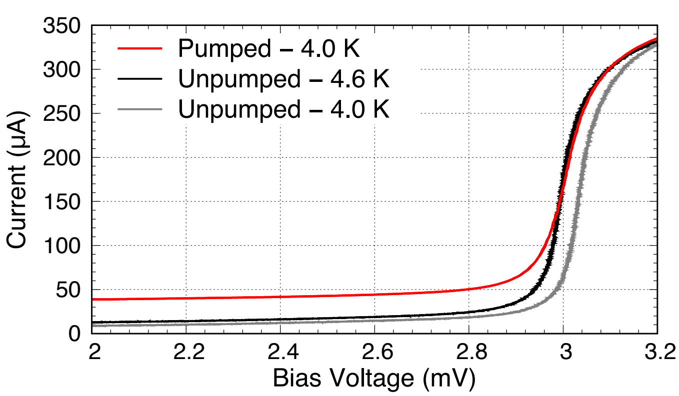

Fig. 2. Plot illustrating how we infer the effective temperature of the tunnel junction by matching the gap voltage of pumped and unpumped IV curves at different block temperature. The temperature shown in the legend indicates the mixer block temperature when the IV curve was taken.

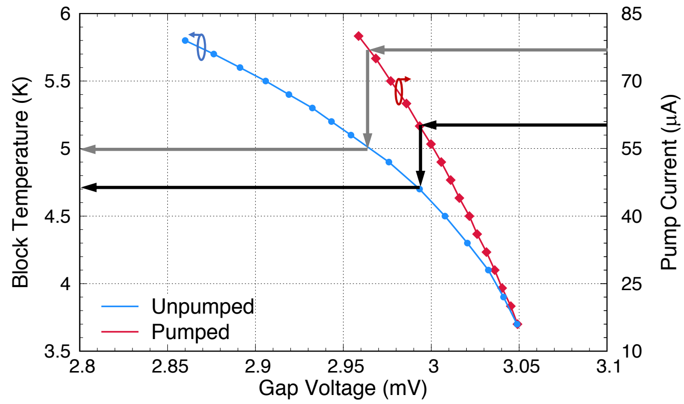

Fig. 3. Relation between the pump current and the effective tunnel junction temperature. The pumped IV curve was measured at a fixed temperature of 3.3 K.

We can also recover the effective junction temperature by correlating the mixer block temperature of the unpumped IV curves with the pump current, measured at the centre of the photon step of the pump curve, instead of the gap voltage. In this case, in addition to the series of unpumped IV curves measured at different mixer block temperature, we further measured a series of pumped IV curves with a fixed block temperature of 3.3 K but injected with LO at different power levels. Fig. 3 shows the relation between the two sets of data, and how we can easily estimate the effective tunnel junction temperature by reading the pump current. As shown in the black arrows, if the pump current is measured at say 57 μA, we can directly infer from the graph that the junction temperature has been heat up to 4.7 K. Similarly as shown in the grey arrows, if the pump current is measured at 72 μA, the effective temperature of the junction must have been increased to 5 K, closed to 1.7 K higher than the mixer block temperature.

III. Conclusion

We have characterised the effective temperature of the hybrid Nb/AlN/NbN tunnel junction fabricated between a NbTiN ground plane and an Al wiring layer, when pumped by a strong LO power operating near 1 THz regime. The increase of junction temperature due to the LO heating was estimated by matching the gap voltage of the pumped IV curve measured at a fixed block temperature, with the gap voltage of the unpumped curve measured at different block temperature. We have shown that the junction temperature can be increased by 1.7 K when the mixer is pumped at approximately 21% of the gap current, which will inevitably affect the performance of the mixer operating at such high frequency.

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