MMA Memo #264

Local Oscillator Power Requirements for ALMA SIS Mixers

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Abstract

We discuss requirements for the local oscillator (LO) power specifically for Nb-based SIS mixers for the ALMA Project. The scheme of the LO power generation / distribution for ALMA receivers is discussed.

LO power for Nb-base SIS mixer

Performance of a SIS mixer is a function of DC bias and applied LO power [1]. We make a number of assumptions to simplify our estimation and to calculate the LO power which is required for optimum SIS mixer operation. First, we assume that the tuning circuit *resonated out* the SIS junction intrinsic capacitance and the junction's quantum reactance is negligible. We take the DC biasing of Nb-based SIS mixer at the middle of the first quantum step below the gap voltage. Parameter α that characterizes the normalized level of LO amplitude across the SIS junction at the optimum LO power level is set to α=1, and $\alpha = eV_{lo} / hf$, where **e** is electron charge, V_{lo} is the amplitude of LO signal, **h** is Plank's constant, and **f** is the operating frequency. If we consider sinusoidal shape of the LO signal voltage across the junction then LO power at the SIS junction can be calculated as $P_{lo} = (V_{lo})^2 / 2\,R_{lo}$. Here, R_{lo} is the DC bias dependent real impedance of the tuned SIS junction with the normal state resistance R_n pumped at level α by LO.

For R_{lo} calculations as a function of frequency **f** we used model SIS junction current-voltage characteristic (IVC) depicted in the Figure 1.

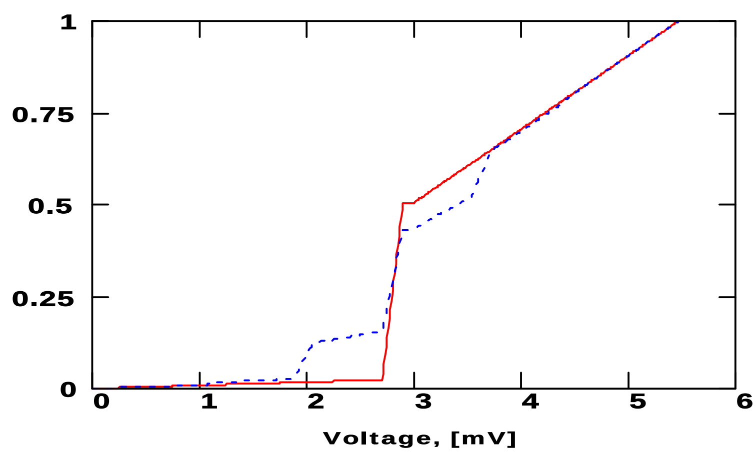


Figure 1 DC IVC (solid red line) of the model SIS junction with R_n=5 Ω, quality factor R_j / R_n=10, the gap voltage V_g=2.8 mV and IVC with LO (dash line, blue) at **f= 200 GHz**, α **= 1**. Note that R_n is defined as the *differential resistance* at voltages above 3 mV.

Using equations from the reference [1] we calculate R_{lo} for different frequencies **f**. The result of the calculation is presented in the Figure 2.

Calculations of the LO power at the SIS junction have been made for R_n**=5, 10 and 15 Ω** (Figure 3). If we fix the junction area, for instance A=4 μm^2, one should think about the three SIS junctions with *different current density* J_c **= 11, 5.5 and 3.7 kA/cm^2**.

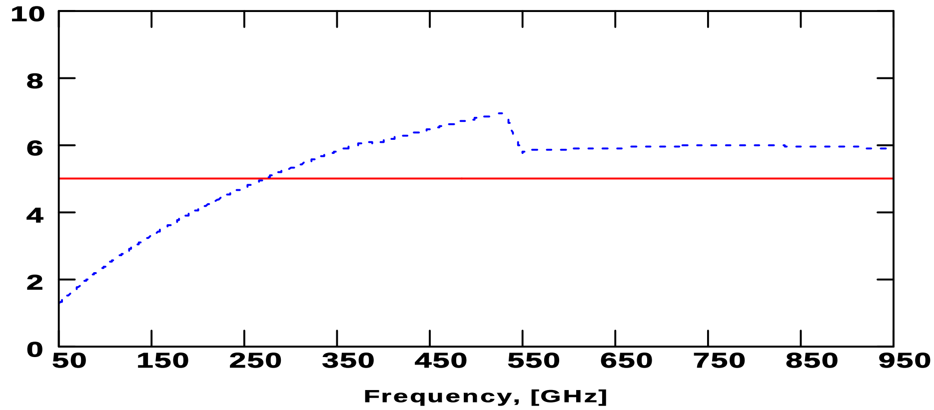


Figure 2 $\mathbf{R_{lo}}$ [Ω] (dash line, blue) for different frequencies **f** of the model IVC SIS junction with $\mathbf{R_n}$**=5 Ω, α = 1**. $\mathbf{R_n}$ is plotted as the solid line (red). The junction biased at the middle of the first photon step. The curve slope onset at about 550 GHz is due to interference with the quasiparticle steps coming from the negative branch of the SIS junction IVC.

Clearly, if one would like to decrease the LO power required to pump a SIS mixer at the optimum level, there are two ways to do it: either the SIS junction with a given area should have lower critical current density $\mathbf{J_c}$ or, for a given $\mathbf{J_c}$, the junction area should be reduced.

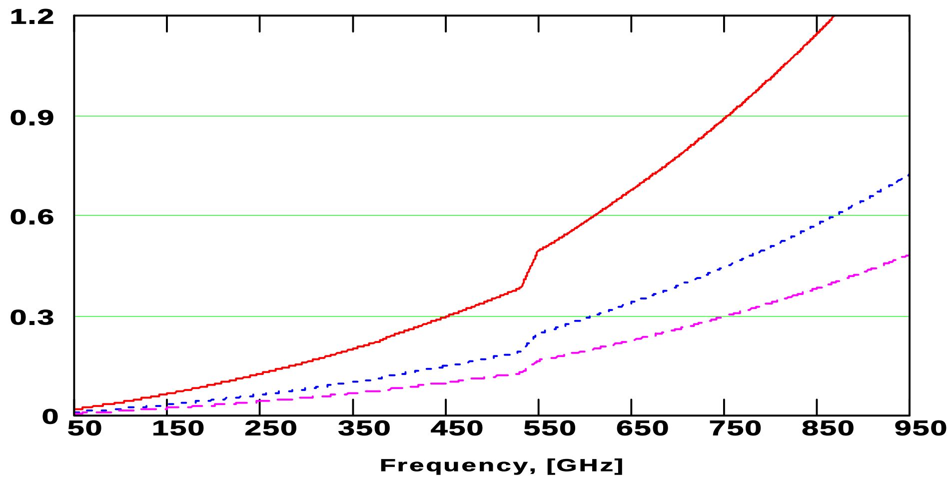


Figure 3 $\mathbf{P_{lo}}$ [μW] for different frequencies **f** of the model IVC SIS junction with $\mathbf{R_n}$**=5 Ω, α = 1** (solid red line), $\mathbf{R_n}$**=10 Ω, α = 1** (dot line, blue), $\mathbf{R_n}$**=15 Ω, α = 1** (dash line, magenta).

The array of N junction will require **N** times more LO power applied, again for a given $\mathbf{J_c}$ and the SIS junction area. For comparison purpose we assumed that, if one would like to replace a single junction with an array consisting of N junctions, the current density of the array junctions should be adjusted to keep the RF matching as for the single SIS junction.

To make our calculation more realistic we should introduce the mixer RF loss which is always the case and it typically increases with the frequency. We take into account the loss associated with the mixer block (waveguide loss, waveguide-to-substrate coupling and corrugated horn-to-antenna beam coupling). For that purpose we empirically added a linear increase of the RF loss [dB] vs. frequency in the range 50-950 GHz and we assumed the power coupling loss of 8 dB at 950 GHz. The result of the calculation is shown in the Figure 4.

The loss in the SIS tuning circuit has drastic increase above the gap frequency of the superconducting material, $\mathbf{F_g}$ (F_g = 675 GHz for the model junction). That causes severe degradation of the SIS mixer performance and rises the required LO power further up. Various solutions to that problem have been suggested, including using of a normal metal [2] or different superconducting material, e.g. NbN [3] or more recently NbTiN [4]. This new material based SIS mixers are under development and we optimistically do not add any loss due to the tuning circuit to our estimation of the required LO power compare to the assumed above 8 dB at 950 GHz.

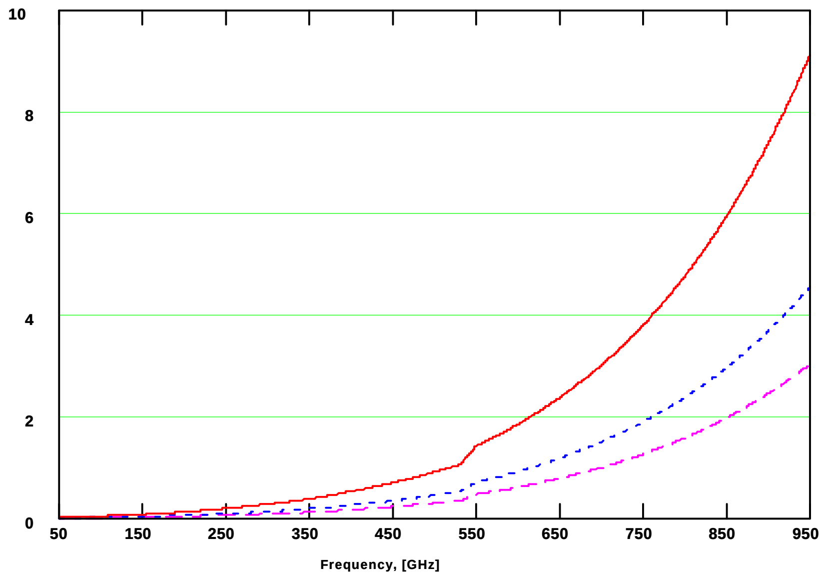


Figure 4 $\mathbf{P_{lo}}$ [μW] for different frequencies **f** based on the model IVC for SIS junction with $\mathbf{R_n}$**=5 Ω, α = 1** (solid, red line), $\mathbf{R_n}$**=10 Ω, α = 1** (dot line, blue), $\mathbf{R_n}$**=15 Ω, α = 1** (dash line, magenta). The RF coupling loss had been added compare to Figure 3. The loss is assumed to increase linearly from 0 to 8 dB in the 50-950 GHz frequency range.

We can expect some extra-loss for a fixed-tuned SIS mixer compare to that with tuning by, e.g., backshort. The SIS integrated tuning circuit is optimized for the required frequency band (sometimes as wide as ±25% of the center frequency). The complexity of the tuning circuitry should be compromised with the yield during the mixer chip fabrication and the capacitance that the RF tuning circuit will add at the intermediate frequency [5]. A ripple in the matching within the tuning band of the mixer can add up ±0.5 dB coupling loss at some frequencies in the band with more loss towards the tuning band ends.

SIS junction is a device with one RF terminal and, except for a balance design, the LO power should be injected directly at the signal input. If a tuned diplexer is used for the LO injection, the power required from the LO source will be as shown in the Figure 4 with difference for the insertion loss of the diplexer itself and the LO power guiding system loss.

LO injection scheme for a fixed-tuned SIS mixer is typically a beam-splitter or a directional coupler with *insertion loss* for the signal of 1% (or less, as low as possible) and for the LO the insertion loss of 99% (or more). The balanced SIS mixer (see for example [6]) can have lower LO insertion loss. However, one should be careful with the background thermal noise possibly leaking though the LO feed. If the balanced rejection is less than 20 dB the background noise may degrade the mixer performance. If we assume that the SIS junction parameters (area and normal state resistance) are identical for non-balanced and balanced SIS mixer then the two SIS junctions of the balanced mixer will require twice of a single junction mixer LO power with some extra loss in the LO distribution circuitry. Taking, e.g., 13 dB available from the balanced mixer common mode rejection we will need 7 dB (300 K background) attenuation for the background noise suppression plus about 3-5 dB loss in the distribution circuitry and another 3 dB for the two SIS junctions of the balanced mixer. The mixer design similar to [7] with the two fixed-tuned SIS mixers for SSB operation will also require 3 dB more LO power compare to a non-balanced mixer with some loss in the LO distribution circuitry. Again, for comparison purpose we assumed that the junction area and $\mathbf{J_c}$ are identical for all types of the mixers. *Summarizing*, the loss in the LO injection via beam splitter or directional coupler for a fixed tuned SIS mixer are expected to be *within 15 - 28 dB* range with **average 21 dB insertion loss for the LO injection** (assuming not more than 1% of the signal loss due to LO power injection).

The result of the calculation (Figure 5) shows that the specified LO power for MMA frequency range, P_{lo} = 100 μW [8], is well enough for frequencies up to 700 GHz. For the upper part of ALMA receiver band, above 700 GHz, the required LO power for Nb-based fixed tuned mixers is about 3 times higher.

In the discussion above we found that the balanced SIS mixer may have substantially lower LO injection loss, especially if the balanced LO noise rejection is about 20 dB. This could be an advantage assuming limitation of the available LO power. However, the increased RF loss in the superconducting transmission lines above the gap frequency (≈650 GHz) causes penalties in the noise performance of the SIS mixer, especially with relatively complicated distribution circuitry for signal and LO injection that is required for the balanced mixer. Using alternative superconducting material, e.g., NbTiN material will be a big advantage for this type of mixer.

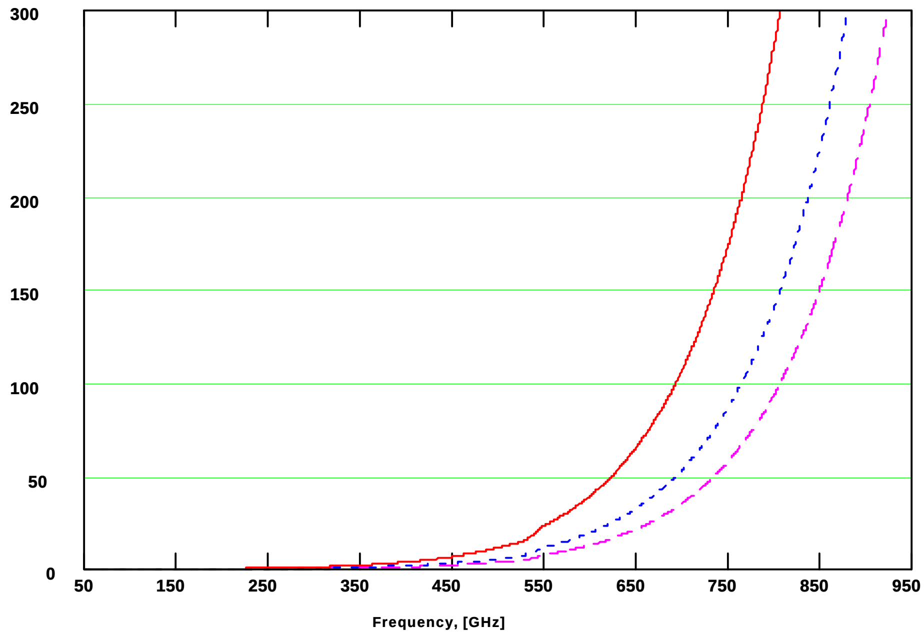
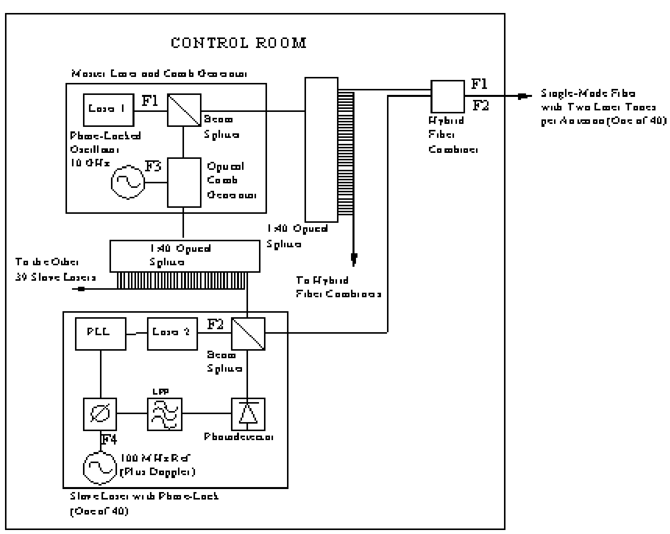


Figure 5 $\mathbf{P_{lo}}$ [μW] for different frequencies **f** for SIS junction with $\mathbf{R_n=5\ \Omega,\ \alpha = 1}$ (solid, red line), $\mathbf{R_n=10\ \Omega,\ \alpha = 1}$ (dot line, blue), $\mathbf{R_n=15\ \Omega,\ \alpha = 1}$ (dash line, magenta). The LO injection loss 21 dB had been added compare to Figure 4.

Scheme Of The LO Power Generation / Distribution For ALMA Project

There are two technologies which are considered for the ALMA Local Oscillator (LO) system recently. The first approach is to use a photonic photomixer to produce LO signal at the desirable frequency as a result of mixing down two laser signals tuned at much higher frequency. In details the physics of the device and its possible use for ALMA Project is outline in references [9 - 11]. Figure 6 from reference [11] illustrates the block diagram for the MMA photonic LO source.



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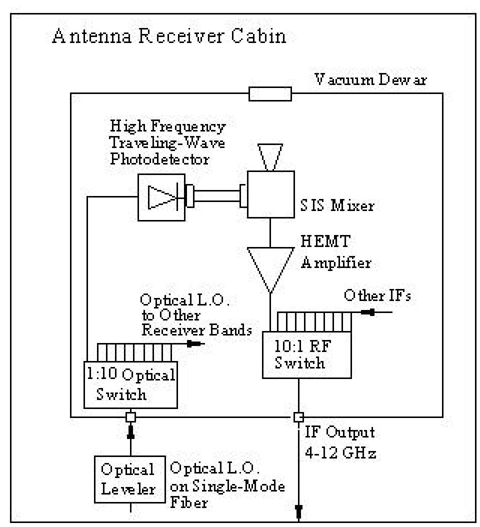

B

Figure 6 Photonic LO oscillator for MMA Project [11]. A - laser signals' source. B - cryogenic photomixer integrated with SIS mixer.

Perhaps the main advantage to use the photonic LO source is the ease of LO signal distribution over the ALMA site. The phase stability and synchronization are provided by using a single pair of lasers generating LO signal (Figure 6B) and being distributed between the antennas via fiber optical cables and using commercially available components for fiber optic communication. The critical component in this technology remains the photomixer itself. The power available from a single device demonstrated experimentally is of an order of 1 μW [9, 10]. There are certain advantages in the output power if the photomixer device is optimized for a particular frequency band (narrow band design requires a number of such photomixers to cover the entire ALMA frequency range). The output power available from the photonic device needs to be improved to pump existing SIS mixers (Figure 5).

The alternative is multiplier technology employing a combination of a Gunn oscillator and a chain of varactor diode multipliers followed the Gunn oscillator. This is proven technology with LO sources for SIS mixer operating almost everywhere. Recently it was suggested a modification where the Gunn oscillator is replaced by a combination of low level phase stabilized source followed by a harmonic generator. This source at n-harmonic frequency feeds HEMT power amplifier generating the required power level of the signal to pump the multiplier chain. The block diagram of the amplifier-multiplier source is depicted in the Figure 7 [12].

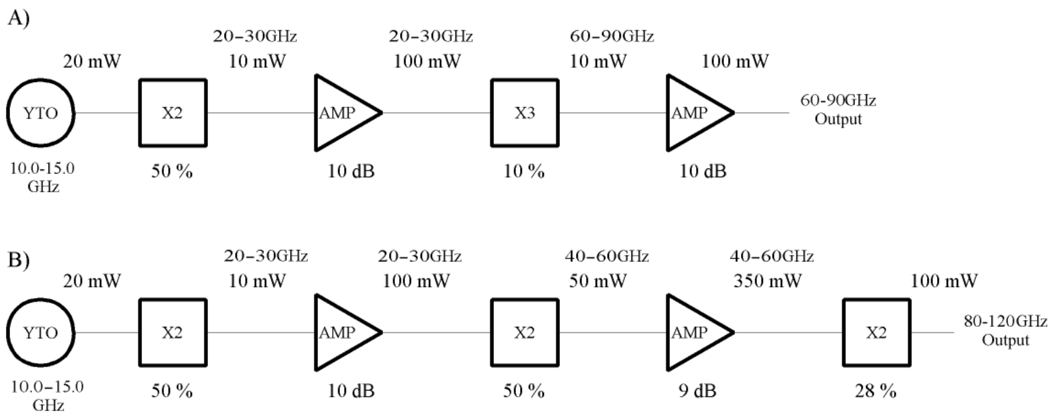

Figure 7 Combined amplifier-multiplier source from [12]

Potential advantages of using the latter configuration were seen as increased power level to pump the multiplier stages and eliminating PLL system, which is required to stabilize Gunn oscillator otherwise. This technology was reported to be successfully demonstrated by JPL/Caltech group [13] though with Gunn oscillator. Advantages of the multiplier source are sufficient power, proven reliability and extensive experience in building such sources [14 - 16]. Recent development is focused on improvement of fixed-tuned design and power available at the higher frequencies (above 600 GHz). In regard to the ALMA LO system, employing of the multiplier LO introduces a challenge to provide the phase coherency across the ALMA site.

As we can see the both technologies have advantages and drawbacks. Perhaps, it would be great benefit to merge these two approaches without brining much of the weaknesses. In attempt to reach this objective we suggest to *combine the photonic mm-waves source (40-60 GHz) with the multiplier chain taking use of HEMT amplifier technology* to boost the signal from the photonic source to the level sufficient to pump the multiplier chain. This solution works out the problem of distribution phase coherent LO signal over ALMA site. The power available from the multipliers is sufficient for SIS mixers and possibly will be improved by using cryogenic multiplier [17]. This solution leaves space for future development for both photonic technology, to improve generated power, and for the multiplier technology, to achieve wide-band fixed-tuned multipliers with sufficient power at sub-mm wavelengths.

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