Celestial Signals

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Low Noise Amplifiers, the future for Future Millimetre-wave Radio Astronomy Receivers?

Authors: D. Cuadrado-Calle^{1,2}, D. George², B. Ellison³, G. A. Fuller¹, and K. Cleary⁴.

¹ University of Manchester, Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, Manchester, M13 9PL, UK.

² University of Manchester, School of Electrical and Electronic Engineering, Manchester, M13 9PL, UK.

³ Rutherford Appleton Laboratory, STFC, Harwell, Didcot, OX11 0XU, UK.

⁴ California Institute of Technology, Department of Astronomy, Pasadena, CA 91125, USA.

1. Introduction

Radio emission emanating from celestial sources was first detected by Karl Jansky during the 1930s. Using primitive radio instrumentation coupled to a relatively small aperture telescope, Jansky mapped portions of the Milky Way and established the field of radio astronomy. Thus was born a branch of modern astrophysics that has allowed study of radio emission from cosmic sources and revolutionised our understanding of the universe.

During the intervening years since Jansky's pioneering work, increasingly large and complex radio observatories have been created that have extended the observational spectral range from metre scale wavelengths to the far infrared (FIR). The most recent and largest of these observatories is the Atacama Large Millimetre and submillimetre Array (ALMA); a complex multi-telescope (multi-antenna) interferometric instrument located in the Atacama Desert of Chile at an elevation of 5,000 m [1][2][3]. Situated at a dry and high-altitude site where atmospheric transmission and seeing are excellent, and furnished with sensitive state-of-the-art sensor technology and utilising high-speed digital signal processing techniques, ALMA is providing a detailed view of our galaxy and external galaxies within the millimetre and submillimetre wavelength range as never seen before.

ALMA's core detector technology utilises advanced superconductor-insulator-superconductor (SIS) tunnel junction mixers cooled to ~ 4 K, and configured as heterodyne receivers operating at a lowest frequency of 84 GHz and extending to near 1 THz. However, advances in transistors fabrication are now allowing the creation of low noise amplifiers (LNAs) with performance properties that challenge SIS technology in terms of sensitivity and usable bandwidth to frequencies as high as 116 GHz. This technical advancement offers the prospect of achieving excellent system sensitivity without the need for 4 K cooling; a technically challenging task in any environment and one that introduces substantial operational demands at a remote site. For instance, it could allow the merger of two previously defined ALMA receiver bands, Band 2 (67 GHz to 90 GHz) and Band 3 (84 GHz to 116 GHz) into a single super-broadband LNA-based instrument [4]. This technical leap would enhance scientific data throughput by increasing the observational efficiency of the array, and also provide a degree of operational advantage by releasing an otherwise occupied 4 K slot (Band 3) in the receiver front-end cryogenic system.

Within the following sections, we present a comparative study between LNA and SIS mixer technologies specifically addressing the frequency range from 75 GHz to 110 GHz, designated as W-band, which is of relevance to ALMA and wider use. The respective principles of operation of each technology are briefly described, and typical instrumentation specifications such as device and system noise, bandwidth, and stability, are presented.

2. State-of-the-art W-band detecting technologies.

a. LNAs with High Electron Mobility Transistors

Low noise amplifier (LNA) technology has advanced very considerably during the past two decades, which is exemplified through improvements in device sensitivity, gain and frequency of operation. Key to performance enhancement has been the development of transistor technology with reduced feature scale, e.g. gate length, and use of higher carrier mobility semiconductor materials, e.g. InP. For instance, at frequencies around 100 GHz, the InP High Electron Mobility Transistor (HEMT), also known as Heterostructure Field Effect Transistor (HFET), represents a major improvement in transistor configuration. When operating at cryogenic temperatures, typically 20 K, delivers a device noise performance only a few times that of the quantum limit [5], i.e. the noise level imposed by the Heisenberg uncertainty principle [6].

The HEMT structure consists of epitaxially grown layers of semiconductors each with a highly controlled composition of thickness and doping [7]. Together, these semiconductor layers form a field effect transistor (FET) and a typical structure is shown in Figure 1 [8] [9].

Figure 1. InP HEMT structure. Image credit: [8].

The conduction band interface between the InAlAs and InGaAs layers forms a triangular well of energy levels in which there exists a high electron density and current. Within this region the charge carriers (electrons) can move freely as a 2-dimensional electron gas (2DEG) with extremely high mobility. This latter feature leads to a device that exhibits low noise and high frequency of operation, usually defined in terms of the cut-off frequency (f_T), i.e. the frequency at which the device's current gain becomes unity.

HEMTs are three port devices that possess gate, source and drain terminals. The current flow from source to drain (I_D) is controlled via the gate contact through the InGaAs high mobility channel. By applying a signal voltage (V_{GS}) to the gate terminal, the drain current is varied and signal amplification (gain) occurs. The DC performance of HEMTs is typically represented through their I-V curves, an example of which is shown Figure 2.

Figure 2. I-V curves of a typical InP HEMT at 22 K ambient temperature. Image credit: [10].

The example transistor characteristics shown in Figure 2 correspond to an InP HEMT at 22 K ambient temperature. Due to the low compression point of cryogenic InP HEMTs, it is common to operate these devices at low drain-source voltage V_{DS} , which results in low power consumption.

Designing LNAs for operation within the millimetre-wave range is highly challenging due to difficulties with transistor fabrication. Moreover, at frequencies higher than 70 GHz equivalent circuit models are increasingly inaccurate and improved electromagnetic simulators must be employed that account in more detail for device physical properties. However, a rapid recognition of the importance of the millimetre and submillimetre-wave region to areas of science, e.g. astronomy and Earth observing, communications and defence has focused considerable technical effort towards achieving related solutions to these problems. For example, a reduction of the gate length of HEMT devices to less than 50 nm, and the fabrication of T-shaped gate terminals that provide low gate resistance and parasitic capacitance have allowed for the development of LNAs with an f_T of 420 GHz [11] and at lower frequencies with noise characteristics that challenge SIS mixer technology [12].

The prospect of using HEMT LNAs as millimetre-wave sensors is thus a reality. Furthermore, MMIC (Monolithic Microwave Integrated Circuit) HEMT LNAs can be screened cryogenically on-wafer, thereby allowing their characteristics to be determined prior to assembly into integrated modules. For this reason, along with additional advantages of wide operational temperature range, fabrication repeatability, mass production and low cost potential, and ultra-wide bandwidth, see section 3d, we believe that LNA technology will eventually become the primary form of receiver front-end within W-band and at frequencies as high as 150 GHz. Some works such as [13] have already demonstrated LNAs with a noise temperature as low as 46 K at 152 GHz and are a good indicator of this approach. We believe the adoption of LNAs will likely be in all ranges of instrumentation from single channel receivers to future large-scale, kilo-pixel, and focal plane arrays.

Figure 3. Photograph of a Monolithic Microwave Integrated Circuit (MMIC) LNA for ALMA band 2+3 with the cover removed.

b. SIS mixers

SIS mixer technology has provided millimetre and submillimetre-wave astronomers with superb sensitivity across a wide observational spectrum extending to frequencies above 1 THz. The advent of the technology in the early 1980s not only revolutionised the capabilities of existing facilities, but dramatically expanded the performance expectation for new observatories to be located on Earth, e.g. ALMA, deployed on aircraft, e.g. SOFIA [14], or in space, e.g. Herschel HIFI instrument [15]. Astronomers were thus provided with a detection tool of unparalleled sensitivity and that has gained substantial maturity through the outstanding work of numerous researchers and their institutes.

The SIS device takes advantage of unusual properties exhibited by certain metals and their alloys when cooled to a very low temperature. Below a critical temperature, T_c , they lose all electrical resistivity and in principle present no barrier to current carrier flow and also expel any magnetic flux. These two phenomena categorise the materials as superconductors. If two superconductors are placed in close proximity to each other (few nm scale separation) then a further phenomenon of paired electron (Cooper pair) tunnelling, the Josephson effect [6], can occur between the two and a Josephson junction is thus formed. In the SIS device, separation between the two superconductors is achieved by use of a thin, typically 3 nm wide, insulating barrier. The device is biased by the application of a DC voltage such that Cooper pairs are split and the tunnelling is by the single electron quasiparticles.

A modern SIS material structure consists of typically Nb-AlO_x-Nb, which must be cooled to an ambient temperature of 4 K or less in order to function properly. When cooled, the SIS device exhibits a very sharp non-linearity between applied DC voltage (V) and current (I) [16]. A diode-like current voltage relationship results from this quantum-mechanical process. Application of high frequency signal (ν) imparts additional energy $h\nu$, where h is the Planck constant, to the quasiparticles. This leads to the device I-V acquiring a series of steps whose voltage width is proportional

to the frequency of the incident photon steam and results in a process called “photon-assisted-tunnelling”.

The above process is most simply represented through the energy band model shown in Figure 4, in which the zero voltage paired electron flow is suppressed. Within this model, and with the exception of a small leakage current that arises from a non-ideal operation, there is no tunnelling current for applied voltages less than the energy gap as defined by $2\Delta/e$, where Δ is the material energy gap in electron volts, and e is the electron charge. An applied voltage bias that exceeds $2\Delta/e$ results in a very rapid onset of current flow and an extremely sharp region of non-linearity. When considered as a classical non-linear device, frequency mixing of the incident signal with a local oscillator (LO) will result in frequency down-conversion of the incident signal. Thus, SIS technology can be used to form the key mixing component of a heterodyne receiver. A quantum mechanical evaluation of the SIS mixer performance predicts properties of low conversion loss, potentially with signal gain, and a low (Shot) noise contribution that is limited by signal quantisation – the quantum limit.

Figure 4. (a) SIS mixer diagram. (b) I-V curve of the SIS junction. The dashed line is the behaviour when there is no local oscillator; the solid line shows the behaviour with LO power supplied. Image credit: [6].

At frequencies between 75 GHz and 1 THz SIS mixer technology provides superb sensitivity, and has been demonstrated to frequencies as high as 1.4 THz [17], albeit with degraded performance due to material energy gap limitations. In addition, SIS mixers offer the advantage of being tunable over a wide input frequency range ($\sim 30\%$) [6][18], their required local oscillator power is usually less than 1 μW [6], and are low-cost in mass production. As an example of the performance that this technology can offer in the W-band frequency range, the SIS mixer for ALMA band 3 (84 GHz to 116 GHz), which is shown in Figure 5, and its corresponding 4-8 GHz IF preamplifier are reported in [19]. The SIS + IF LNA block features an approximate SSB noise temperature of 30 K, gain of 33 dB, and image rejection of 15 dB.

Figure 5. ALMA Band-3 SIS mixer with cover removed. Image credit: [19].

On-wafer screening of SIS junctions is not straightforward and so the SIS mixer must be first assembled and cooled to 4 K to verify performance and stability. Whilst this has not been a prohibitive requirement for projects such as ALMA, it is of increasing significance as we approach the era of kilo-pixel arrays. However, the main issue with SIS technology is the need for cooling to 4 K which places a cryogenic demand that can, and does, limit applications. For instance, deployment of 4 K cooling technology in space, whilst proven, is exceedingly complicated and costly and limits the potential for many applications, including interplanetary probes.

3. Comparison between SIS and LNA technologies

a. Structure of the receiver

A common characteristic of radio astronomy receivers operating in the millimetre wave range is a requirement to cool them to cryogenic temperatures in order to reduce their electrical noise contribution. In the case of SIS devices, however, they will only function as mixers below the superconducting material T_c , and achieve best performance at an ambient temperature lower than $T_c/2$, typically 4 K for Nb devices. This operational requirement severely contains the application of SIS technology as complex and expensive 4 K coolers are required, or large quantities of liquid helium. LNAs, on the other hand, can operate at any ambient temperature whilst achieving excellent performance at an ambient temperature well above 4 K, typically between 15 K and 20 K [20], and thereby considerably easing cryogenic system requirements. The wide and more relaxed cooling requirements of LNAs are therefore a considerable advantage when considering their deployment and system integration. This becomes particularly important when considering future space-based instruments.

The structure of radio astronomy front-end receivers has a high influence in the overall instrument noise. In typical radio astronomy front-ends the incoming radio frequency (RF) signal is coupled to the receiver through a feed horn antenna that is designed to interface with the telescope optical

arrangement. The received signal is very weak, i.e. < -100 dBm/GHz, and comparable to the receiver noise given by the Friis formula:

$$T_{RX} = T_1 + \frac{T_2}{g_1} + \frac{T_3}{g_1 g_2} + \dots + \frac{T_n}{g_1 g_2 \dots g_{n-1}} \quad \text{Eq. 1}$$

where T_{RX} is the noise temperature of the receiver, i.e. the temperature of a perfectly matched load at its input that would give rise to an equivalent amount of noise in a noiseless receiver [6], and T_n and g_n are the noise temperature and the gain of the stage n . From Equation 1, the most influential elements on the noise temperature of a receiver are those closest to the input (lower sub-indexes in the equation). Therefore, to unmask the signal from the receiver noise, a very sensitive component is mandatory in the receiving chain, after the horn. In order to further enhance overall system sensitivity, radio astronomy receivers are often configured to measure both signal polarisation components. This requires the use of two receiver systems (LNA or SIS) in combination with an input polariser, e.g. a free-space wire grid or orthomode transducer (OMT). However, for the purpose of simplicity, we only refer to single polarisation systems in this study.

For an LNA receiver front-end architecture, the amplifier boosts the signal from the feed horn, typically by a factor of 1,000 (30 dB), and the subsequent output is frequency down-converted to an intermediate frequency (IF) by a following mixer and LO combination. Additional IF signal conditioning, including further amplification and filtering, prepares the signal for final detection and processing. The receiver back-end configuration extracts the required information and can range from a simple square-law detector, which provides an integrated signal measurement, to a complex high-speed digital signal processor providing high-spectral resolution information [6]. Figure 6 shows the typical front-end diagram of an LNA-based radio astronomy receiver front-end.

Figure 6. Simplified LNA front-end receiver diagram.

For the SIS receiver front-end architecture, the mixer directly down-converts the RF signal to the IF range. Once again, the IF signal is further amplified and filtered in order to meet with the specifications of the final stage of detection. Figure 7 shows a simple diagram of a typical SIS receiver. Although it is not shown in the diagram, it is not uncommon to include a $50\ \Omega$ impedance cryogenic isolator between the SIS mixer and the IF LNA to improve the matching between these two components.

Figure 7. Simplified SIS front-end receiver diagram.

b. Noise

System noise is the most critical parameter in evaluating the performance of a radio astronomy receiver as it limits observational sensitivity, i.e. the ability to detect the required signal. For a total power radiometer, system sensitivity can be estimated from Equation 2:

$$\Delta T = \frac{T_{SYS}}{\sqrt{B \cdot \tau}} \quad \text{Eq. 2}$$

where ΔT is the output root mean square (rms) noise fluctuation, T_{SYS} is the system noise temperature, τ is the integration time and B is the bandwidth of integration. The weakest detectable signals are a few times, typically five, the output rms noise fluctuation. System noise (T_{SYS}) includes antenna noise and receiver noise (T_{RX}). From Equation 2, it is clear that minimising it is a priority, particularly as integration time and bandwidth are often parameters established by observational constraints such as the need to spectrally resolve features or the timescale of atmospheric or instrumental stability.

In the previous section, we established that the noise in a receiver chain is given by the Friis formula for noise as shown in Equation 1. When ignoring insertion loss arising from interface optics, the total system noise in typical LNA and SIS receivers, $T_{LNA\ RX}$ and $T_{SIS\ RX}$ respectively, can be calculated from Equations 3 and 4. The subscripts in these equations correspond to the elements shown in the diagrams of Figure 6 and 7.

$$T_{LNA\ RX} = T_{LNA} + \frac{T_{Schottky}}{g_{LNA}} + \frac{T_{IF\ stage}}{g_{LNA} g_{Schottky}} \quad \text{Eq. 3}$$

$$T_{SIS\ RX} = T_{SIS} + \frac{T_{IF\ LNA}}{g_{SIS}} + \frac{T_{IF\ stage}}{g_{IF\ LNA} g_{SIS}} \quad \text{Eq. 4}$$

In the above examples, the front-end LNA or SIS mixer is the primary source of noise and it is essential that this contribution is minimised in each case. However, although the noise contribution of the subsequent IF chain is divided by the gain of either the LNA or SIS device, because g_{LNA} is $\gg 1$, typically 1,000, and g_{SIS} is < 1 for stable operation, it is clear that the LNA provides a potential

advantage over the SIS mixer when considering the noise generated by the complete system. That is, the noise contribution of the IF chain has substantially less impact on the system noise for an LNA receiver than it does for an SIS equivalent, and the following approximations can be made:

$$T_{LNA\ rx} \approx T_{LNA} \quad \text{Eq. 5}$$

$$T_{SIS\ rx} \approx T_{SIS} + \frac{T_{IF\ LNA}}{g_{SIS}} \quad \text{Eq. 6}$$

State-of-the-art LNAs and SIS mixers achieve a minimum noise temperature above four times the quantum limit [5]. This is shown in Figure 8, which contains a comparison of the noise temperature of some state-of-the-art W-band LNAs and SIS mixers compiled from the literature. To allow a representative comparison, the noise of the SIS mixers includes the contribution of the IF LNA according to Equation 6. Additionally, some of these devices were measured as part of a receiver chain with other components whose noise contribution has not been corrected for. The caption of Figure 8 provides some estimated corrections that should be applied in each case. Noteworthy is the superior noise performance of current LNA technology compared with the SIS devices operating in the 100 GHz frequency range.

Figure 8. Noise temperature of some state-of-the-art W-band LNAs and SIS mixers. Noise data of SIS mixers obtained from their reference paper. Mixers [24] and [25] are sideband-separating (SSB). Reported data for mixer [26] is double side-band (DSB) and has been converted to single side-band (SSB) as: Noise Temp (SSB) $\approx$ 2 x Noise Temp (DSB).

Superscripts meaning is as follows:

^A Uncorrected for contributions of dewar window and horn, which are estimated in 2-3 K.

^B Uncorrected for contributions of dewar window, I/R filter, horn and OMT, which are estimated in 4-5 K.

^C Uncorrected for contributions of dewar window, I/R filter and horn, which are estimated in 2-3 K.

c. Stability: gain fluctuations.

Gain fluctuations within an LNA arise from thermal and chaotic effects which cause fluctuations in the number of available charge carriers and in their mobility [27]. They impact system stability and, ultimately, system integration time. With improved noise performance the influence of gain fluctuations becomes a dominant factor in achieving improved signal-to-noise, and therefore, its effect must be carefully considered when designing and implementing receiver system front-ends.

Equation 2 described the sensitivity of an ideal radio astronomy receiver. However, if the receiver's gain, g , is not perfectly constant, a false signal of rms amplitude ΔT will be produced at the output of the receiver as shown in Equation 8:

$$\Delta T = T_{SYS} \left(\frac{\Delta g}{g} \right) \quad \text{Eq. 8}$$

where the term $\Delta g/g$ represents the gain fluctuation. If this effect is included in the receiver's sensitivity equation, as signal fluctuations and gain fluctuations are independent random processes, their variances add in quadrature and the practical total-power radiometer can be calculated as shown in Equation 9 [6]:

$$\Delta T' = T_{SYS} \cdot K \cdot \sqrt{\frac{1}{B \cdot \tau} + \left(\frac{\Delta g}{g} \right)^2} \quad \text{Eq. 9}$$

where K is a constant that depends on the receiver configuration.

The output variations produced by gain fluctuations are indistinguishable from comparable changes in the system temperature produced by the astronomical source [28]. Thus, it is important to minimise them so that Equation 10 is satisfied as closely as possible.

$$\left(\frac{\Delta g}{g} \right)^2 \ll \frac{1}{B \cdot \tau} \quad \text{Eq. 10}$$

The total gain stability of a cryogenic LNA can be specified in terms of its Spectrum of Normalized Gain Fluctuations (SNGF), which is modelled by an expression of the form:

$$S(f) = b \cdot \left(\frac{1}{f} \right)^\alpha \quad \text{Eq. 11}$$

where $S(f)$ is the SNGF with units $\text{Hz}^{-1/2}$, f is the frequency, and b and α are the parameters of the model. As a figure of merit, for ALMA the proposed gain fluctuation specification in a frequency range of 1 Hz is $1 \times 10^{-4} \text{ Hz}^{-1/2}$ [29].

Gain fluctuations in a radio astronomy receiver are due to a combination of factors. Some are intrinsic to the LNA or SIS mixer device, and some are extrinsic to it. In the case of LNA-based receivers, the gain fluctuations should be dominated by the intrinsic stability of the RF LNA. Because LNAs have gain, the gain fluctuations of the subsequent (Schottky) mixer become less important. There is only sparse data for the intrinsic gain fluctuations of RF LNAs operating in the W-band. In [30], a 10-stage 80 GHz LNA with 50 μm gate width transistors is shown to have a total gain fluctuation of around $5 \times 10^{-4} \text{ Hz}^{-1/2}$ @ 1 Hz. Another work [31], points out that for a 6-stage HEMT LNA with 50 μm gate width transistors operating at 100 GHz, a total gain fluctuation of around $3 \times 10^{-4} \text{ Hz}^{-1/2}$ @ 1 Hz is not an unreasonable estimate. These values are higher than the ALMA specification; however, the amplifiers in these examples have a large number of stages, which increase the gain fluctuations, and are not state-of-the-art devices. Recent (as yet unpublished) measurements [32] indicate that current state-of-the-art LNAs with 3 or 4 stages can meet the gain stability requirement for ALMA.

In the case of SIS mixers, the theory for their intrinsic gain fluctuations is not developed yet [27]. Some studies suggest that the gain fluctuations of an SIS receiver are consistent with the intrinsic gain fluctuations of the cryogenically cooled IF amplifier attached to the mixer, and other extrinsic causes of mixer gain variation such as changes in local oscillator power supplied to the mixer or changes in the physical temperature of the SIS device [27] [33]. Typically, IF LNAs suffer less from gain fluctuations than RF ones, as they employ larger transistor sizes, and gain instability is inversely proportional to the size of the transistors [27]. For instance, in [29] a 3-stage 4-12 GHz IF LNA for ALMA with 150 μm gate width transistors shows gain fluctuations of $4.5 \times 10^{-5} \text{ Hz}^{-1/2}$ @ 1 Hz. However, it is the extrinsic factors which dominate the stability of the SIS receiver [34]. This is demonstrated in [33], where the maximum allowed temperature fluctuation for an LNA and SIS mixer was found to be 106 mK/s and 48 mK/s respectively, given the requirement for both to produce receiver gain drifts of less than $14 \times 10^{-4} \%$ per second. SIS receivers have a stronger dependence of gain fluctuations on temperature than LNAs receivers. From [34][35] it is also clear that SIS receivers are very sensitive to local oscillator power variations, and in [27] it is demonstrated that an LO power error of 10% leads to a gain reduction of 1%.

In conclusion, if intrinsic gain fluctuations in the SIS mixer are small compared to those in the LNA, SIS mixer receivers can in principle be more robust against gain fluctuations when compared to LNA receivers [31], but special care has to be taken to provide optimal conditions that minimise extrinsic sources of instability in the SIS receivers. This includes physical temperature and LO power stability, but also improved bias electronics, careful elimination of ground loops, and reduction of cryocooler vibrations [34]. Depending on the science goal, there are different strategies for improving receiver stability such as use of Dicke-switching radiometers, correlation radiometers, continuous comparison radiometers, etc [6][28]. However, these architectures are more complex, and in some cases have other drawbacks such as loss of efficiency.

d. Bandwidth

In order to observe the broad range of spectral emission and absorption signatures emanating from the interstellar medium and extragalactic sources, LNA and SIS heterodyne receiver systems must be able to encompass a broad spectral range. Ultimately, the input frequency response of an LNA or SIS mixer limits the signal input range. However, the components that comprise the IF of the system, including the signal processing back-end spectrometer, limit the instantaneous bandwidth and more often than not impose the primary restriction. As an example, the ALMA observatory receivers have a maximum instantaneous observational bandwidth of 8 GHz. A wider spectral range can be observed by tuning of the SIS mixer LO or, in the case of an LNA receiver, the LO as a part of the signal down-conversion chain. Tuning the LO is, however, a relatively inefficient method of achieving wider signal coverage as it requires an incremental approach which does not make best use of telescope observation time and also risks missing spectral features. Thus, there is increasing preference and demand for broader instantaneous bandwidth observation and new wideband receivers are consequently being developed.

HEMT LNAs are inherently broadband devices, and the main limitation for their RF bandwidth is imposed by the waveguide interface. For instance, at W-band the standard waveguide is WR-10, and it features a cut-off frequency of 59 GHz, and single-mode transmission below 118 GHz. Hence, if

this waveguide is used, the maximum fractional RF bandwidth would be 68%. Additionally, in order to match the waveguide characteristic impedance to the input impedance of the MMIC, an embedding circuit (typically a waveguide-to-microstrip probe) must be used, and this element also restricts the RF bandwidth. For rectangular waveguides propagating signals in TE₁₀ mode, the waveguide characteristic impedance can be obtained as [36]:

$$Z_{WG} = \frac{\eta}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \frac{2b}{a} \quad \text{Eq. 12}$$

where a and b are the widths of the broad and narrow walls of the waveguide, η is the intrinsic impedance of the material filling the waveguide, f_c is the cut-off frequency of the waveguide and f is the operating frequency. A standard WR-10 waveguide presents an impedance of 702.01 Ω at 70 GHz, 499.55 Ω at 90 GHz, and 439.33 Ω at 115 GHz. The complexity of designing an ultra-wideband embedding circuit is due to the difficulty of matching this broad range of impedances to the input impedance of the MMIC, typically of the order of 50 Ω . Examples of W-band LNAs with more than 40% RF bandwidth are shown in [12] and [23], and 50% in [21].

In the case of SIS mixers, fundamental limitations on matching bandwidth of arbitrary impedances [37] as established by Fano in 1950 has been used historically to determine the theoretical maximum RF bandwidth of SIS mixers. However, in practise, the RF bandwidth of SIS mixers is also limited by the maximum bandwidth of the waveguide, and the difficulty of designing ultra-wideband embedding circuits. In addition, there are also other limits associated to the difficulty of the device fabrication. High RF bandwidths are usually achieved through small device areas which have lower capacitance but are more difficult to fabricate. Small capacitance values will not short circuit higher harmonics produced in the nonlinear junction, and this results in poorer mixer performance. Examples of broadband W-band SIS mixers can be found in [38] with 40% RF bandwidth, and in [19] and [25] with 32% RF bandwidth for ALMA band 3.

As previously mentioned, the IF bandwidth can ultimately limit the instantaneous observational bandwidth. In LNA receivers, the IF bandwidth is not limited by the LNA itself, and when combined with compatible Schottky mixers, very wide IF bandwidths can be achieved relatively straightforwardly. As an example, the commercially available MXP-10 W-band mixer from Millitech has an IF range between 0.1 GHz and 35 GHz. The instantaneous IF bandwidth of SIS mixer receivers is limited by intrinsic parasitics of the junction and RF tuning circuit [38]. The contribution of the junction parasitics can be minimised by reducing the size of the junction or by cascading multiple stages. However, reducing the contribution of the RF tuning circuit is more challenging in practise. An approach to overcome this problem consists of including an IF transformer between the SIS mixer and the IF amplifier as in [39]. In this work, a 220 GHz SIS mixer with an instantaneous IF bandwidth of 14 GHz was recently reported. Nevertheless, this technique is difficult to extend to lower-frequency mixers due to internal resonances of the mixer which limit the available IF bandwidth. To the best knowledge of the authors, at the frequency range of interest for this work, i.e. W-band, current state-of-the-art SIS mixers such as the one reported in [19] for ALMA band 3, achieve a maximum IF bandwidth of typically 8 GHz.

In summary, both SIS mixers and LNAs operating in W-band can theoretically achieve very wide fractional RF bandwidths up to $\sim 70\%$. In practice, however, the main limitation is imposed by the waveguide interface and the embedding circuit. The widest RF bandwidths so far reported for SIS mixers and LNAs operating in W-band are around 40% and 50%, respectively. Concerning the IF range, at present both SIS and LNA receivers can achieve the maximum bandwidth imposed by the state-of-the-art correlators, typically 8 GHz. However, if new back-ends with wider bandwidths were developed in the future, LNA receivers would have potential for covering wider IF ranges than SIS receivers.

e. Cryogenic system

Receiver sensitivity has improved very considerably thanks to the advancements in cryogenically cooled SIS mixers operating at ~ 4 K, and LNAs operating at 20 K ambient temperature. Cryostats have been, and remain, a core component in modern radio astronomy receivers operating in the millimetre-wave frequency range.

In the past, there has been an important difference in maintenance cost between 4 K and 20 K cryostats due to helium consumption. However, with modern closed cycle cryogenics, the need for supply of liquid helium has substantially reduced, and at ground-based observatories the maintenance cost of 4 K and 20 K cryostats is not so different. Key differences between these two systems are exposed when considering likely future advancements required for astronomy; for instance, spaceborne applications and large format heterodyne focal plane arrays [40]. With these latter applications demands on cryocooler heat lift, and reliability, will be stringent, as will overall power consumption efficiency. Operation at higher ambient temperature provides very considerable advantage in this regard as suggested by Figure 9, where the cooling power of two large capacity commercial cryocoolers is represented as a function of the temperature, and by Figure 10 [41], which based on a study survey of hundreds commercial cryocoolers, shows an estimation of the input power versus operating temperature with the cooling power as a parameter.

Figure 9. Cooling power of two large capacity commercial cryocoolers.

Figure 10. Estimated input power versus operating temperature with the cooling power as a parameter, varying from 0.3 W to 100 W. Image credit: [41].

4. Conclusions

Radio astronomy observatories operating in W-band (75 GHz to 110 GHz) have typically utilised SIS-mixers as core detecting technology to achieve the best possible noise performance. The best example is the ALMA telescope, in Chile, which utilises advanced SIS mixers operating from 84 GHz up to 1 THz. Recent technical advancements in HEMT technology are, however, beginning to challenge this position with the development of LNAs with exceptional noise performance at frequencies above 100 GHz. Because of this, the choice between using SIS mixers and HEMT LNAs at these frequencies is less distinct and factors other than the relative noise contribution must be considered such as: the structure of the receiver, gain fluctuations, maximum RF and IF bandwidths, and cryogenic system needs. Within this brief comparative study of SIS mixers and HEMT LNAs we introduced basic concepts and key features and requirements that are necessary to evaluate the most convenient technical architecture for future millimetre-wave instruments. The choice is, of course, very much dependent upon the exact application, but we anticipate that in years to come LNAs will find increasing application at frequencies above 100 GHz, particularly as receiver pixel densities increase and demand for wider instantaneous bandwidth grows.

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