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Ultra-wideband Cryogenic Low Noise Amplifiers: a Cool and Crucial Component for Future Submillimetre Radio Telescopes

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This article reports on the evolution in designing state-of-the-art cryogenic, wideband, low-noise amplifiers as used in the intermediate frequency stages of ALMA receivers. The most recent designs are presented which demonstrate exceptional bandwidth and noise performance; those are crucial in enabling the planned ALMA Wideband Sensitivity Upgrade.

Introduction

For radio telescopes like the Atacama Large Millimeter/submillimeter Array it is crucial to optimise performance parameters such as sensitivity and observation bandwidth in order to keep pace with the developing needs of the astronomical user community. Since current receiver systems at these short wavelengths already demonstrate very low noise performance, on the order of a few times the quantum limit hν/k, further improvement of that parameter is practically very limited. An alternative way to enhance sensitivity is to increase the instantaneous bandwidth. This must be achieved across the entire astronomical signal chain, both the analogue signal path and the digital signal processing, interfaced by suitable high-speed digitisers (Quertier et al., 2021). In the analogue section of the receiver, a humble but critical component in this respect is the intermediate-frequency cryogenic low-noise amplifier. In this article we report on the latest developments that enable further increase of the instantaneous bandwidth.

Maximising the instantaneous bandwidth

Almost since the beginning of radio astronomy one of the permanent items in the wish list of radio astronomers has been to enlarge the instantaneous bandwidth processed by the instruments, which is intrinsically linked to an increase in observation efficiency. For continuum (total power) observations this means increasing the sensitivity or needing less integration time, since fluctuations in power measurements diminish in proportion to the square root of the bandwidth. For spectral-line observations a wider frequency range is accessible at once so more lines or transitions of the same species can be observed in less time, and blind redshift observations are facilitated. In the submillimetre wavelength range, where ALMA stands out, this allows delving deeper into the origins of galaxies and performing much faster astrochemical surveys of a spectrum plagued with a forest of lines which provide invaluable information about the physical-chemical conditions in the objects observed.

The major millimetre radio telescopes, including the Institute de Radioastronomie Millimétrique (IRAM) Northern Extended Millimetre Array (NOEMA) and the Submillimeter Array (SMA), are implementing this increased bandwidth upgrade. The Atacama Large Millimeter/submillimeter Array (ALMA) will also follow this strategy, as set out in its Development Roadmap 2030 (Carpenter et al., 2019) and detailed in the Wideband Sensitivity Upgrade (WSU) initiative (Carpenter et al., 2022).

Figure 1 is a generic, simplified block diagram of a typical receiver architecture as used in submillimetre radio telescopes like ALMA bands 3 and up. It is based on the heterodyne principle whereby the incoming submillimetre radio frequency (RF) signal is down-converted to a lower frequency, the intermediate frequency (IF), which is typically below 20 GHz, and which can be more easily amplified before being sampled and quantised by room-temperature electronics to establish a digital representation of the input signal. The mixing and first stages of IF amplification are carried out by devices developed specifically for this application and cooled to cryogenic temperatures to minimise the self-generated noise.

The sensitivity of the receiver is directly impacted by the noise generated in the signal chain. The cascaded noise performance is given by the expression (Friis, 1946):

$$T_{RX} = T_{SIS} + \frac{T_{IF_1}}{G_{SIS}} + \frac{T_{IF_2}}{G_{SIS} \times G_{IF_1}} + \ldots$$

Where T_{SIS}, T_{IF_1}, … and G_{SIS}, G_{IF_1}, … represent the equivalent noise and gain respectively of the components in the signal chain of Figure 1. The formula provides insight into how the noise contributions of those components close to the input are dominant. Considering that the typical submillimetre-wave mixing devices[a] attenuate the incoming signal ($G_{SIS} < 1$), the noise contribution of the first IF low-noise amplifier (LNA) becomes even more pronounced and should be minimised to obtain a more sensitive receiver.

The other crucial parameter, the instantaneous bandwidth, is very much determined by the components in the analogue signal chain, in particular the IF amplifiers

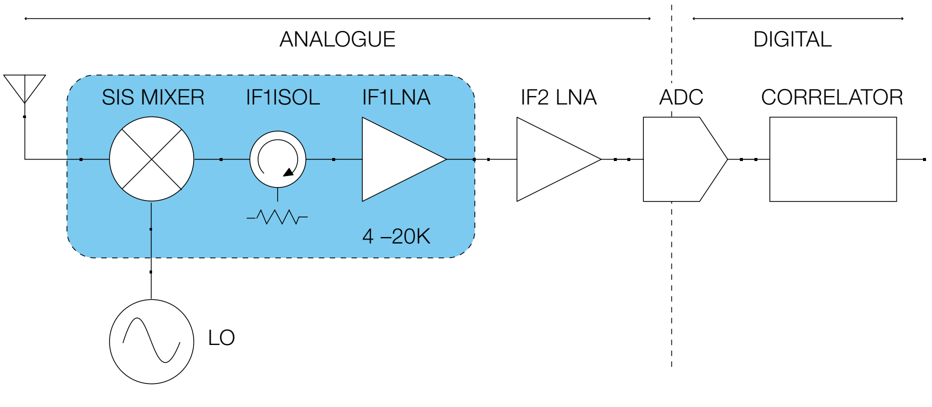

Figure 1. Generic block diagram of a typical submillimetre heterodyne receiver signal chain. There is usually one channel per polarisation.

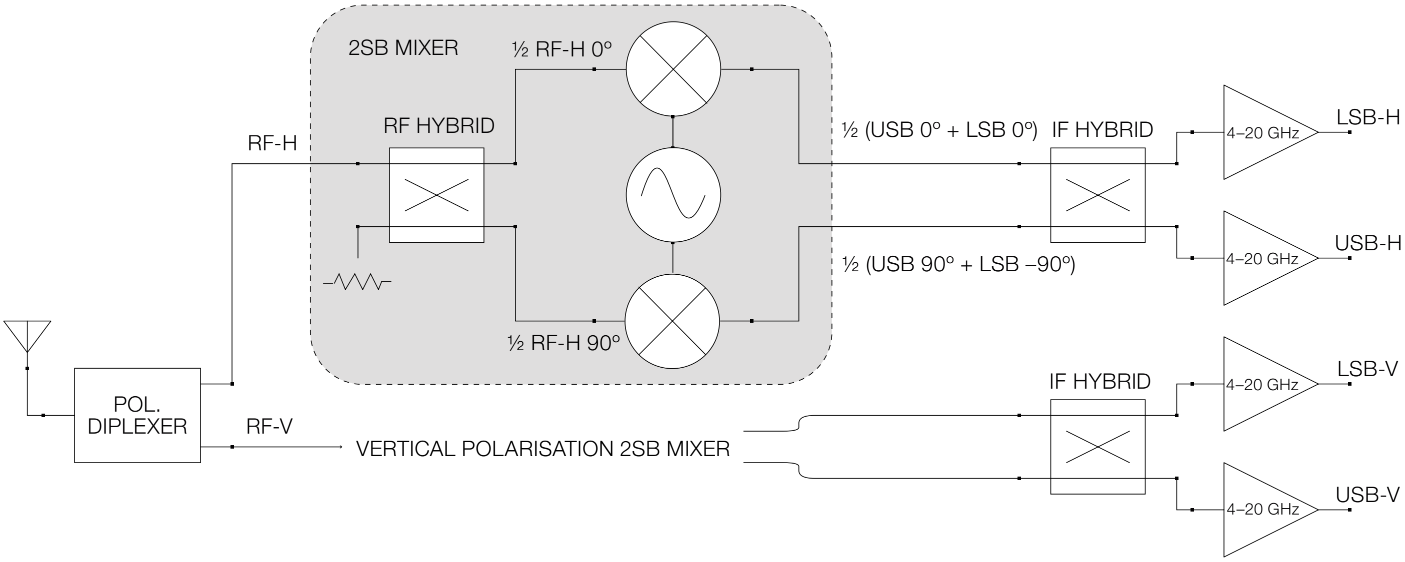

Figure 2. Simplified block diagram of a submillimetre receiver front-end based on 2SB mixers. The RF and IF quadrature hybrid couplers introduce a 90° phase delay in the coupled paths. USB and LSB refer to the upper and lower IF sidebands respectively. Note that the instantaneous bandwidth available to be processed is four times the IF bandwidth, totalling 64 GHz.

and the analogue-to-digital converters (ADCs).

Analogous to the visible spectrum, which extends over one octave, the maximum RF bandwidth that can be processed by the input mixer is usually limited in practice to less than one octave in frequency by the physical constraints of the components (waveguides, for example). The problem with a heterodyne receiver that is intended to cover a large bandwidth, comparable to that which could be handled by the input mixer, is that the number of octaves to be processed at the IF can be prohibitively high and this becomes a challenge for the design of the components in the IF chain.

The ALMA strategy to multiply by four the present instantaneous bandwidth consists of (a) doubling the present maximum 8 GHz bandwidth per IF channel to achieve 16 GHz, and (b) extending the use of sideband separating or 2-sideband (2SB) mixers to all ALMA bands[b]. Figure 2 presents a block diagram of a submillimetre receiver front-end based on 2SB mixers. This scheme can separate the upper and lower sidebands generated in the mixing process into two IF channels by means of two mixers and two quadrature hybrid couplers which introduce selective 90° phase delays to finally cancel the undesired sideband in each channel. The ALMA upgrade aims for a 64-GHz band to be processed in the correlator (2 polarisations × 2 sidebands × 16 GHz).

State of the art and requirements

The struggle to increase instantaneous bandwidth has been going on for the last few decades. Figure 3 shows how the instantaneous bandwidth of the most advanced instruments at each epoch has been evolving. In the 1990s the typical value for the first IRAM receivers was of the order of 1 GHz. The development of the HIFI submillimetre receivers for ESA's Herschel mission set the ambitious (at that time) goal of 4 GHz per channel. A few years later, in 2005, an even more ambitious target of twice that value (8 GHz per channel) was established for ALMA and most bands still retain that value.

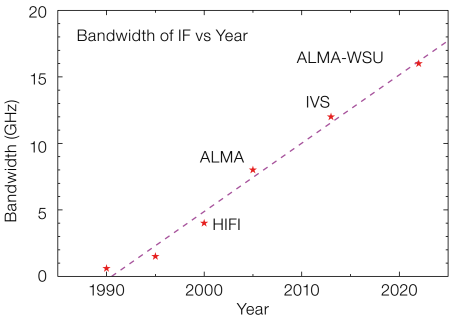

Figure 3. Evolution of the typical instantaneous bandwidth of state-of-the-art radio telescopes over the last 30 years.

The LNA laboratories at Yebes Observatory have promoted this evolution, developing, among others, the cryogenic amplifiers that set the standards in the aforementioned instruments. ALMA bands 5, 7 and 9 are equipped with cryogenic LNAs (CLNAs) designed in Yebes (López-Fernández et al., 2006). Although a significant number were manufactured in its labs, most of the production was completed by a firm that received expertise and technology transfer from Yebes.

However, to be effective the LNA bandwidth expansion should be accompanied by other performance benchmarks. Obviously the noise temperature of the amplifier has to be as low as possible, given its prominent role in the overall receiver sensitivity. Its gain must be high enough that the contribution to the receiver noise from warm electronics is negligible (following equation 1) and sufficiently flat to cope with the limited dynamic range of the ADCs. The power dissipation is restricted by the cooling power of the refrigerator. This fact is especially critical for submillimetre-wave receivers with superconducting mixers which only operate below 4.2 K, or in case of focal-plane arrays (multipixel receivers) with a large number of cryogenic amplifiers.

Finally, a crucial but frequently overlooked parameter is the degree to which the amplifier is matched to its input and output loads, usually measured by the reflection coefficients. A poorly matched amplifier would reflect a relevant fraction of the incident power, producing standing waves along the input line which will translate into a ripple in the output noise temperature and power. This problem was traditionally solved by introducing an isolator between the mixer and the CLNA, as in most of the current ALMA bands (see Figure 1). However, ultra-wideband isolators (Zeng et al., 2018) are critical components to avoid in cryogenic receivers, as they are bulky and introduce significant losses, degrading the system noise temperature. Additionally, a 2SB mixer scheme relies heavily on a well-matched amplifier to achieve a high image rejection ratio (IRR), that is, a proper cancellation of the image (upper or lower) frequency band, as illustrated in Figure 2.

When ESO, in the framework of its Technology Development Programme, set the goals for the next generation of ALMA CLNAs, it became clear that some trade-offs would be necessary, as the requirements far exceeded the state of the art. The challenge was not only to design a CLNA with twice the maximum bandwidth of the current generation ALMA amplifiers, but also to do so with numbers for noise temperature, gain flatness and input reflection typical of narrower-band cryogenic amplifiers.

The most competitive published ultra-wideband cryogenic amplifier results with similar noise temperature lack sufficient bandwidth and, moreover, have their Achilles heel in a poor input reflection: see, for example, Nilsson et al. (2014) for the 6–20-GHz band, later improved by the Low Noise Factory AB in Sweden, or Cha et al. (2018) for the 0.3–14-GHz band. These two conflicting requirements, namely noise and input reflection, are possibly the most difficult to meet in a wide-band LNA.

Transistor development

The key component in any modern microwave amplifier is the active semiconductor device, which is usually some type of transistor. A successful amplifier design revolves around making a number of cascaded stages of these devices operate as close as possible to their optimum to obtain their maximum gain and minimum added noise. Other cryogenic amplifying technologies with near quantum-limited noise are either intrinsically narrowband (solid-state masers) or still not sufficiently mature (travelling-wave kinetic inductance parametric amplifiers).

Since the turn of the century the devices of choice for extremely low-noise amplification at microwave frequencies are either GaAs or InP high-electron-mobility transistors (HEMTs), a type of field-effect transistor based on heterostructures with enhanced electron transport properties. InP is an exotic material that is difficult to handle and not easily available commercially. The mainstream GaAs HEMTs were developed first, and there is a prosperous semiconductor industry mass-producing them for many commercial and military applications at an affordable cost. However, the very best results we need are consistently reported using InP technology. Cooling these transistors to cryogenic temperatures further boosts electron transport and reduces the thermal noise generated by parasitic elements, and when combined with a careful design, enables an order of magnitude improvement in the equivalent noise temperature of the amplifier (see the excellent review by Pospieszalski, 2005).

A breakthrough in cryogenic amplifier performance such as demanded by ALMA is not possible without a substantial development of the present InP HEMTs. Very few foundries in the world are capable of producing InP devices. All current ALMA amplifiers feature transistors from the two US foundries (Northrop Grumman Space Systems and HRL Laboratories). With the aim of having an independent, flexible, and accessible supplier of InP transistors in Europe (without the severe import restrictions on US InP technology), Yebes Observatory began a partnership with the Swiss Federal Polytechnic Institute (ETH) 25 years ago that has found its natural continuation with Diramics AG, a spin-off from ETH that produces InP transistors using the same facilities. This collaboration was initially financially supported in part by several ESA projects and more recently by ESO.

Over the past five years we have focused on the development of transistors for the IF range, trying to improve the noise performance and to solve the chronic problem of very high-frequency oscillations. This issue tends to be worse for the best devices and it is aggravated at cryogenic temperatures. Through a slow iterative process, changes in the epitaxial material and the layout structure were proposed, implemented, and tested. On-wafer cryogenic noise measurements of transistors are not accurate enough, hence the devices were evaluated and modelled by testing them in the first stage of a well-known LNA in the Yebes labs. The resulting optimised devices are clearly less prone to auto-oscillation, avoiding the need to only use certain stable bias points that are not necessarily the best in other respects. Furthermore, a very considerable reduction in noise temperature was confirmed, between 15% and 20% depending on the frequency. An additional advantage of these improved devices is that the optimum noise is reached at a lower bias setting, thus dissipating less power. It is typical of well-behaved transistors to display their best performance for lower drain currents. These results put Diramics at the forefront of InP transistor development for IF, ahead of the traditionally superior American foundries.

Figure 4 shows a picture of an optimised device with a gate geometry appropriate for use in the first stage of the ultra-wideband amplifier (the first stage is the most important in terms of noise). It is presented in die form, suitable for wire bonding and independent testing.

LNA design

As regards the fabrication and assembly technology used, microwave amplifiers can be implemented in hybrid circuits (also known as ‘chip & wire’) or in monolithic microwave integrated circuits (MMIC). The former make use of microwave substrates and chip passive components interconnected by bond wires to achieve the matching of the different transistor stages and to realise the DC bias circuits, while the latter integrate most of this circuitry in a single chip. The MMIC option has advantages, especially at the higher microwave frequencies, where size

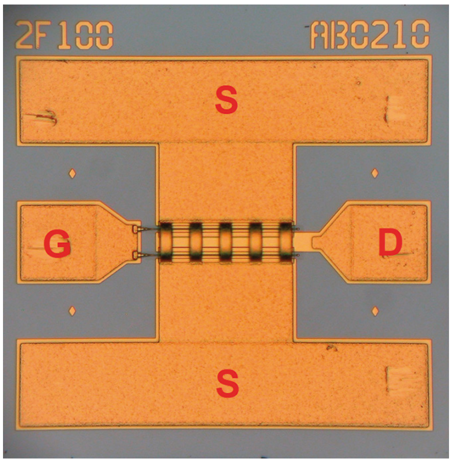

Figure 4. Microphotograph of the 350 × 350 × 100 μm die of the Diramics InP HEMT with 2 × 100 μm gate finger in 100-nm technology. This device is used in the first stage of the 4–20-GHz amplifier and was the outcome of a long term joint development effort between Diramics and Yebes. The transistor terminals (gate, drain and source) are labelled with their initials. Note the five air bridges connecting the source pads.

is a problem owing to the parasitics, and for applications for which a large number of units is demanded. However, for our prototype it is much more convenient to rely on a hybrid design because it is cheaper and faster to produce, modify and tune (an MMIC requires a complete iteration cycle with the foundry). It also allows different transistor technologies to be used for each stage and presents lower losses in the critical input matching circuit, usually implemented by microstrip lines.

Another important design choice is where to place the targeted 16-GHz-wide band. At the present development stage of the ALMA WSU (Carpenter et al., 2022) we are still on time to influence this system-level decision. On the one hand, the upper band limit is constrained by the noise temperature achievable, since it increases almost linearly with frequency. On the other hand, the lower band limit restriction comes from the maximum fractional bandwidth (FBW, defined as the ratio between the central frequency and the bandwidth, usually expressed as a percentage) that permits matching at the level required for this project. The input impedance of HEMT devices is very reactive at low frequencies. Matching in a wide band becomes increasingly difficult for large FBWs. A reasonable compromise was found in the 4–20-GHz band. Note that this represents an FBW of 133% or 2.3 octaves.

The problem of matching is pivotal in the design of an ultra-wideband CLNA. The conditions required by the first stage transistor to minimise the reflected power and deliver the minimum possible noise are different and the strategies for designing a matching network that transforms and brings them together are frequency-dependent and fail in such wide bands. Therefore, to address the stringent requirements for noise and input reflection, the first-stage transistor gate size was carefully selected to favour the matching in the 4–20-GHz band, and a very simple input network was devised. A progressive compromise for the noise mismatch at the lower band end must be tolerated to ensure an acceptable noise performance at the higher end. The other stages can compensate the gain rolloff; nevertheless, it is difficult to separate the role of each stage in this design, as opposed to narrower-band amplifiers.

The intensive use of simulation tools required was supported by a systematic and painstaking process of selection and modelling of components at cryogenic temperature.

The bias networks feed the extremely sensitive HEMT devices with DC power and protect them from electrostatic discharge. They also contribute to the stability of the transistors with high-value resistors that usually dissipate a significant amount of power. We have been able to reduce this fraction to just 15% while still ensuring that the amplifier is unconditionally stable.

A picture of the final prototype is provided in Figure 5, where it is compared with the three times bulkier CLNA used in ALMA bands 5 and 7. Nevertheless, the identical assembly processes, the use of similar microstrip substrates, similar connectors and equivalent gold-plated aluminium modules make them quite alike.

Results in the 4–20-GHz band

The results shown in Figure 6 demonstrate that it is possible to achieve state-of-the-art noise temperature in a 16-GHz-wide band with an input reflection low enough to guarantee excellent matching with the mixer and high IRR without the need for an isolator, which would penalise the system in complexity and sensitivity.

Noise temperature is compared at 15 K ambient with the current ALMA CLNAs. The measurements at 5 K ambient are more representative of the operating conditions of the amplifier, which will be placed in the 4-K stage of the cartridge, and yield an average of 3.7 K, below the goal of 4 K. It is remarkable that comparable noise values are obtained for an upper passband frequency extending to frequencies two to four times higher than current band 9 and 5/7 amplifiers, and with an input reflection below –15 dB, to our knowledge never before achieved in this frequency range. The noise results were confirmed using two independent methods. Yebes Observatory has a long history as a reference lab for cryogenic noise measurements, a slippery field where all too often numbers coming from different institutions differ significantly because of the difficulty of performing accurate measurements.

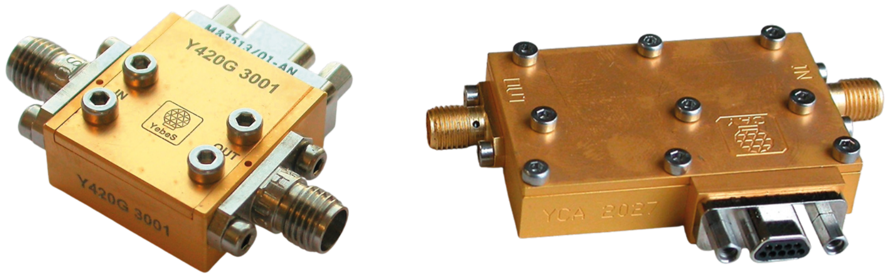

Figure 5. Comparison of the newly developed 4–20-GHz CLNA prototype for the next generation of ALMA receivers (left) with one of the 4–8-GHz CLNAs actually installed in ALMA band 5 and 7 cartridges (right). Both are made of gold-plated aluminum and their sizes are 21 × 20 × 9 mm and 46 × 29 × 9 mm, respectively.

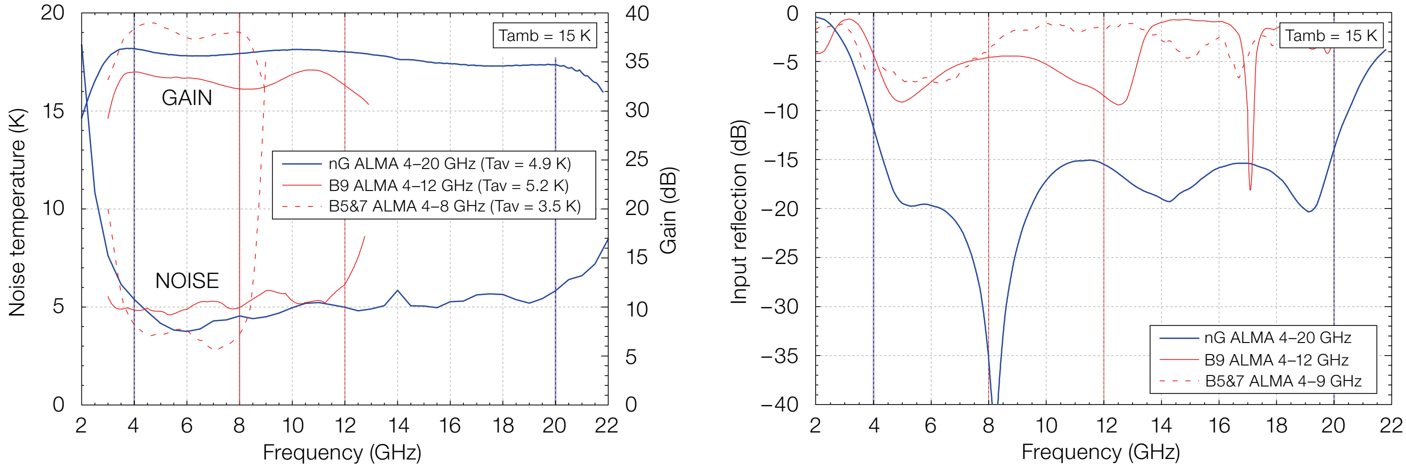

Figure 6. Performance at 15 K ambient of the prototype developed in the 4–20-GHz band (in thick blue) compared with a typical current 4–8-GHz CLNA of ALMA bands 5 and 7 (in dashed red) and 4–12-GHz CLNA of ALMA band 9 (in solid red). Left: noise temperature and gain. Right: input reflection. Average noise temperature at 5 K ambient is 3.7 K. The noise performance of the new amplifier is similar, despite its much wider bandwidth and being designed to achieve excellent input reflection.

The prototype also met the expectations in power dissipation (8 mW), gain flatness (< 1.8 $\mathrm{dB_{pp}}$) and output reflection (< –15 dB).

Future prospects

ESO has recently awarded Yebes Observatory its proposal of a new ALMA Development Study for the “Development of InP MMIC based Wideband Low-Noise Amplifiers for the Next Generation ALMA Receivers” within which we plan to advance Diramics MMIC technology and translate the current design into a monolithic circuit. If successful, the resulting chips could be useful for a prospective production phase of ALMA receivers. Furthermore, considering our recent and promising results of performance with ultra-low power dissipation, they could enable the implementation of ultra-wide band focal plane arrays.

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Notes

[a] Superconductor-Insulator-Superconductor (SIS) tunnel junction mixers.

[b] Presently, ALMA bands with 4-GHz IF channels have 2SB mixers, while bands with 8-GHz channels have classical DSB mixers. The total IF band to process is 16 GHz in both cases. See Tan et al. (2004).

ESA/NASA

This image from the NASA/ESA Hubble Space Telescope shows the central region of the rich globular star cluster NGC 3201 in the southern constellation Vela (The Sails).

A star that has been found to be orbiting a black hole with four times the mass of the Sun lies close to the centre of this picture.