PROCEEDINGS OF SCIENCE

Amplifiers for Radio Astronomy Receivers

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One of the most fundamental elements used in Radio Astronomy receivers are Low Noise Amplifiers (LNAs). The specifications used by the engineers are often hard to understand to astronomers with a pure scientific background. This paper is addressed to young astronomers willing to understand the fundamental concepts in this field, introducing them to the terms used by the engineers to specify the performance of LNAs and some of the problems found in practice. This document contains only a summary of the main concepts. The details of the examples shown in the oral presentation have been eliminated by lack of space.

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1. Introduction

In general terms, an amplifier can be defined as any active device or circuit that uses a small amount of energy (input) to control a larger amount (output). Amplifiers, in analog electronics, are very often assumed to be Linear Time Invariant systems which can be completely characterized by its Transfer Function L(f). The Transfer Function can be understood as a complex number which relates the amplitude and phase of the output and the input for a sinusoidal single frequency signal. The magnitude of the transfer function is usually referred as the Gain of the amplifier.

There are many different types of amplifiers to fit different needs, for example, just to name a few:

Low Noise (LNA): used for low signal levels, designed to minimize the noise added by the amplifier. LNAs are fundamental components of Radio Astronomy receiver and are the main topic of this paper.

Power Amplifier: used for high power levels, designed to optimize the linearity.

Servo Amplifier: this term is normally used for power amplifiers used to drive electrical motors in servo controlled loops of machines in which tight control of the speed or position is needed.

Operational Amplifier (OPAMP): Low frequency integrated amplifiers used as building blocks in many analog designs.

Audio, Video (HIFI, TV): Amplifiers used for sound amplification (20-20000 Hz) or for analog video signals (DC-5 MHz)

Radio Frequency **(RF amp)**, Microwave **(MW amp)** and Intermediate Frequency **(IF amp):** These are amplifiers for higher frequencies usually found in radio transmitters or receivers. IF amplifiers are used in heterodyne receivers after the mixer.

Solid state amp, Vacuum Tube (valve) amp: classified according to the type of active devices used. Solid state is the term used for amplifiers based in semiconductor. Vacuum tubes, once the only element used for amplification, are today found only in exotic applications like very high voltage, high power RF amps or audiophile quality audio systems.

MASER, Parametric amps: These very exotic amplifiers were within the first types used to obtain ultra low noise in cryogenic receivers used for Radio Astronomy and Space communications. Nowadays are considered obsolete due to their complex operation and limitations, although the noise results obtained with masers were very impressive, but limited to a narrow instantaneous bandwidth.

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2. Some fundamental concepts

2.1 Decibel (dB) and dBm

The decibel is a logarithmic unit which is often used by engineers for the measurement of the gain of an amplifier. The gain in decibels is given by:

$$G_{dB} = 10 \cdot \log_{10}\left(\frac{P_{out}}{P_{in}}\right) \qquad\qquad G_{dB} = 20 \cdot \log_{10}\left(\frac{V_{out}}{V_{in}}\right)$$

Being P_{out} and P_{in} the power at the output and input port and V_{out}, V_{in} the corresponding voltages. Sometimes a similar unit, the dBm, is used as a measurement of absolute power causing some confusion. The power in dBm is the power referred to 1 mW expressed in dB. 0 dBm is equivalent to 1 mW.

2.2 Reflection coefficient

The reflection coefficient relates the amplitude and phase of the wave incident and reflected by a load. It is a complex, frequency dependant, dimensionless number. If two impedances are complex conjugate then the maximum power from the source is transferred to the load.

$$\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_s}{Z_L + Z_s}$$

$$|\Gamma|^2 = \frac{Power^-}{Power^+}$$

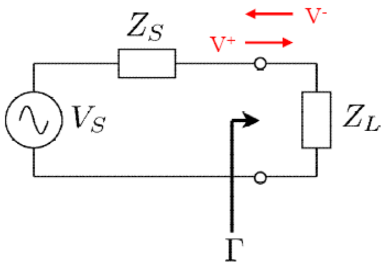

Figure 1: Definition of reflection coefficient of a load of impedance Z_L

Very often the reflection coefficient is expressed in dB. The result is usually referred as Reflection Loss, and is given by:

$$RL_{dB} = -20 \cdot \log_{10}(|\Gamma|)$$

2.3 Scattering (S) parameters

The S parameters are typically used at radio frequencies (RF) and microwaves (MW) to completely describe the behavior of linear electrical two-port networks relating the incoming and outgoing waves. The S parameters are directly measured with an instrument known as Vector Network Analyzer and are very useful in the design and measurement of RF and MW amplifiers.

$$b_1 = S_{11} \cdot a_1 + S_{12} \cdot a_2$$
$$b_2 = S_{21} \cdot a_1 + S_{22} \cdot a_2$$

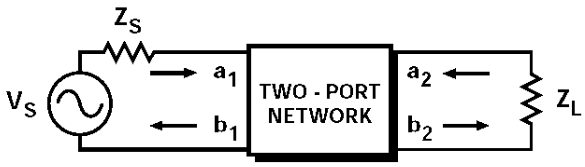

Figure 2: Definition of the S parameters of a two-port network.

S_{11} and S_{22} represent the reflection coefficients at the input and output respectively, while S_{21} and S_{12} represent the forward and reverse gain. The gain of an amplifier expressed in decibel can be calculated as:

$$G_{dB} = 20 \cdot \log_{10}(|S_{21}|)$$

2.4 Noise Temperature

The Noise Temperature is a measurement of the noise generated by an amplifier or receiver expressed as an increment in the physical temperature of the input termination. In other words, the total power at the output of a noisy amplifier with an input termination at physical temperature T_s will be the same than that of an amplifier of the same gain assumed noiseless if the temperature of the input termination is incremented by the noise temperature of the amplifier (T_n). Noise temperature of modern cryogenic amplifiers used in Radio Astronomy receivers is extremely low (a few K) and is difficult to measure accurately using standard laboratory instruments.

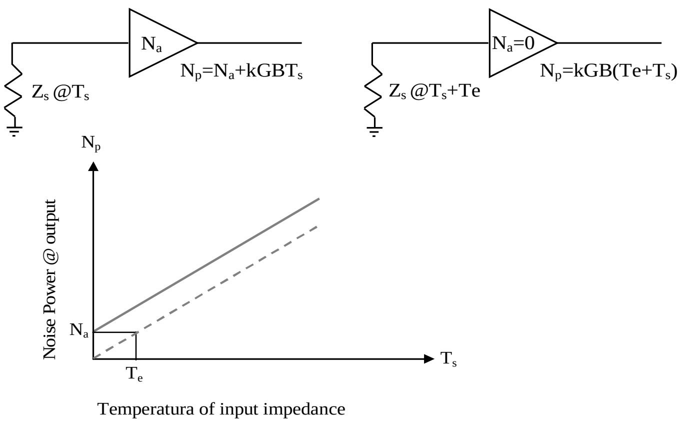

Figure 3: Definition of the Noise Temperature of an amplifier.

The noise generated in electronic devices depends on many factors, being one of them the physical temperature. The best results in modern Radio Astronomy amplifiers are obtained using InP transistors cooled to cryogenic temperature. InP HEMT devices are not commercial and only a few foundries in the word can produce them with the quality needed in ultra low noise cryogenic receivers. The following example shows the dependence of the Noise Temperature on the ambient temperature of a typical cryogenic InP amplifier for the 4-8 GHz band.

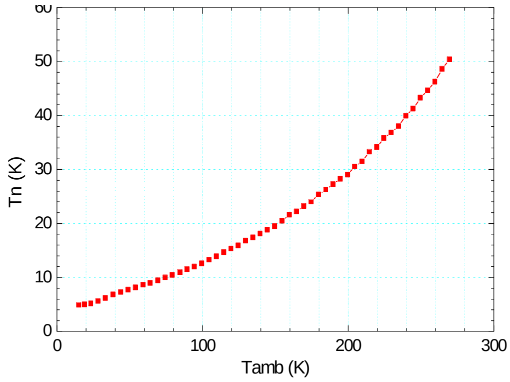

Figure 4: Noise Temperature of a 4-8 GHz amplifier as a function of physical temperature.

2.5 Non-linearity

Amplifiers are normally supposed to be linear. Low noise RF and MW amplifiers usually operate in the linear regime, but in the presence of strong nearby in-band transmitters or interfering signals could enter into the non-linear region. Two measurements are used to characterize the deviation from the linear regime:

2.5.1 1dB compression point

A real amplifier can not deliver unlimited output power. Gain compression occurs when the input power of an amplifier is augmented to a level that reduces the gain of the amplifier and causes a nonlinear increase in output power. The point at which the gain is reduced by 1 dB from the small-signal gain value is the 1 dB compression point.

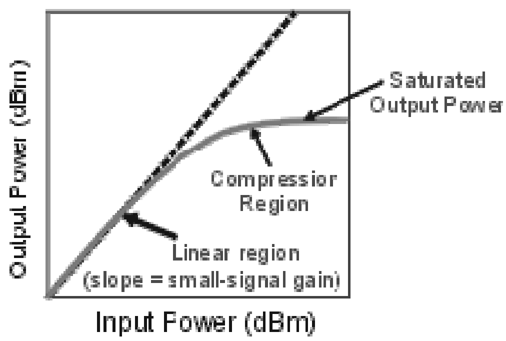

Figure 5: Compression of gain of an amplifier.

2.5.2 IP3: third order interception point

The gain of a non-linear system can be approximated by the Taylor series expansion as:

$$f(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + ... + a_n \cdot x^n$$

Consider an input x(t) consisting in two signals of the same amplitude and different frequency:

At the output many combination of frequencies (intermodulation products) will be found, in particular:

- fundamental (f1, f_2)
- 3rd order ($2 \cdot f_2 - f_1$, $2 \cdot f_1 - f_2$)
- 5th order ($3 \cdot f_2 - 2 \cdot f_1$, $3 \cdot f_1 - 2 \cdot f_2$)
- …

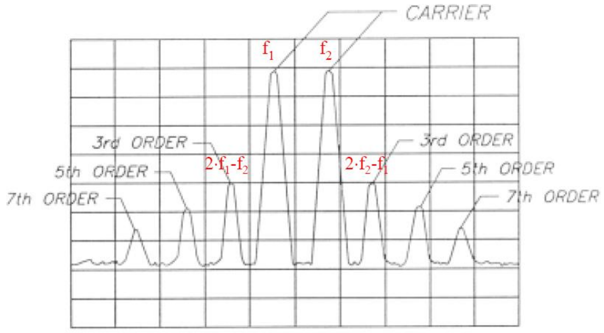

Figure 6: Spectrum showing the typical intermodulation from two pure tones appearing at the output of an amplifier due to the non-linearity.

If we consider variable amplitude of the input signal, the amplitude of the intermodulation products at the output will change at different rates according with their order. As the slope of the fundamental is 1:1 and the slope of the third order is 3:1, at some theoretical point their amplitudes will be the same (see figure). The theoretical point of interception is named 3rd order interception point (TOI or IP3). The value of IP3 is useful in practice in calculating the level of interference due to the presence of strong in band signals.

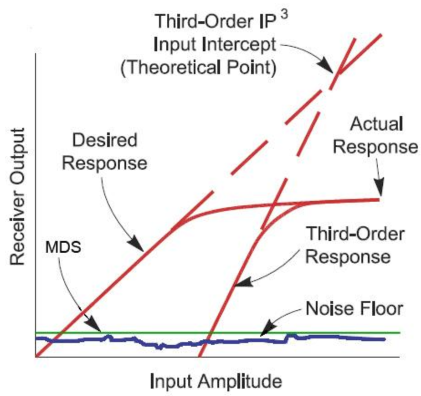

Figure 7: Third order interception point (IP3) obtained from extrapolation of the low-level $A \cdot \cos(2 \cdot p \cdot f_2 \cdot t$intermodulation products.)

3. The problem of Gain Fluctuations

Gain fluctuation is a problem very specific of the Radio Astronomy receivers and particularly severe for the applications requiring continuum receivers with very wide instantaneous bandwidth. The paradigmatic case is Cosmic Microwave Background (CMB) receivers. The problem is that any fluctuation of the gain is indistinguishable from the statistical fluctuations of a random signal integrated a finite time on a limited bandwidth. As modern receivers may have a very wide bandwidth and extremely low noise temperature, the problem of gain fluctuation becomes of great importance, limiting the effective sensitivity for long integration times.

$$P_{out} = K \cdot G_{rf} \cdot B \cdot (T_a + T_r)$$

$$\frac{\Delta P_{out}}{P_{out}} = \frac{k}{\sqrt{Bt}} + \frac{\Delta G_{rf}}{G_{rf}}$$

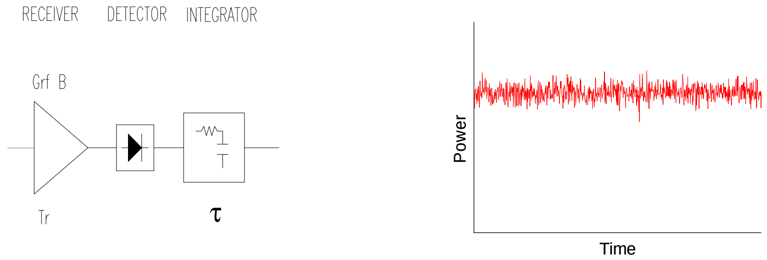

Figure 8: Fluctuations at the output of a receiver due to the effects of the random nature of the input signal and to the fluctuations of the gain.

Gain or power fluctuations can be characterized in the time domain or in the frequency domain. The time domain characterization is preferred by astronomers, since it directly provides the standard deviation (σ) as a function of the integration time. The function used is the Allan Variance defined as:

$$s^2(t) = \frac{1}{2}\left\langle \left(\overline{G}(t+t) - \overline{G}(t)\right)^2 \right\rangle$$

Allan Variance is usually calculated over normalized gain or power. Engineers usually prefer a characterization in the frequency domain, since it can provide some insight in the nature of the fluctuation, and periodic, non-random interferences (1 Hz refrigerator cycle or 50 Hz interferences) are easily detected and can be removed. The characterization used in the frequency domain is simply the Unilateral Spectrum of Normalized Gain (or Power) Fluctuation S(ν) (SNGF). The Allan variance can be calculated from the SNGF using the following relation:

$$s^2(t) = \int_0^\infty S(n) \left| 4\frac{\sin^4(ptn)}{(ptn)^2} \right|^2 dn$$

The next figures show the Allan Variance and SNGF measured for a real 22 GHz Radio Astronomy receiver for several different pre-detection bandwidths. The drift of gain of the receiver appears in the Allan Variance plot as a departure from the ideal 1/BW slope of the radiometric noise. In the frequency domain the two components of the drift with 1/f and 1/f ^{½} are easily identified. The radiometric noise in the frequency domain appears as white noise of value SQRT(2/BW).

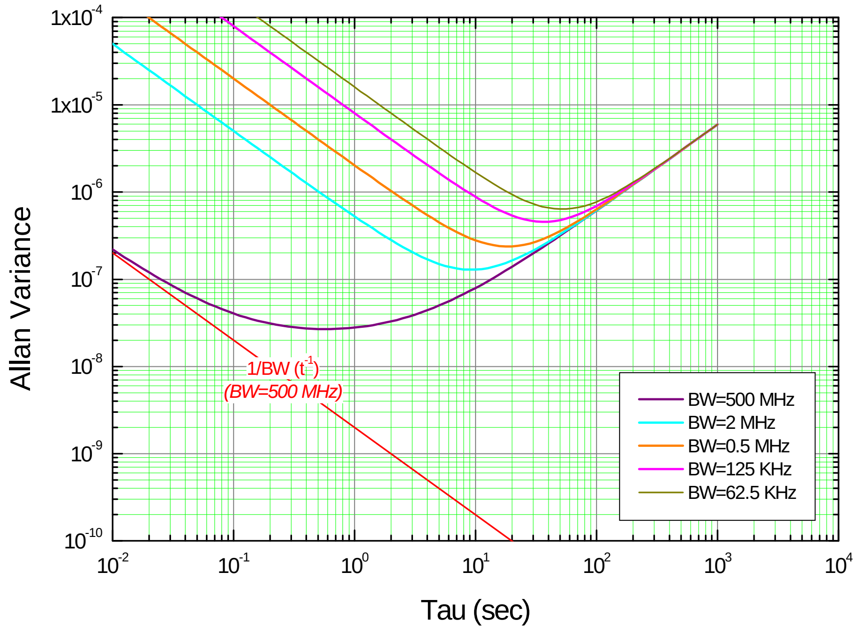

Figure 9: Allan Variance of the normalized power at the output of a 22 GHz receiver for several pre-detection bandwidths.

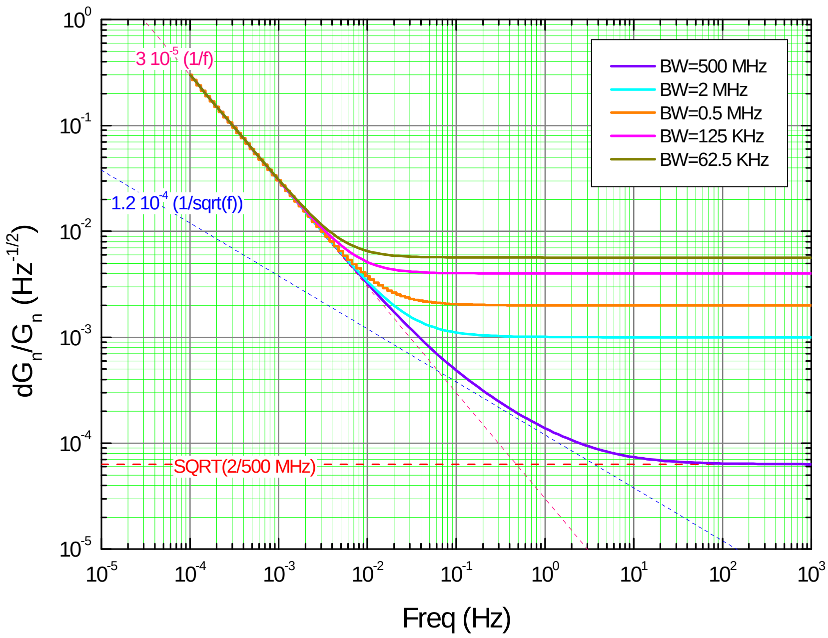

Figure 10: Spectrum of normalized power at the output of a 22 GHz receiver for several pre-detection bandwidths.

4. Cryogenic Low Noise Amplifiers

4.1 Particularities

Cryogenic amplifiers are used in applications were ultimate noise performance is absolutely needed, like Radio Astronomy or ground stations for Deep Space communications. In order to be reliable, a cryogenic amplifier should be mechanically designed to survive extreme thermal cycles. Besides, there are some specific areas in the electrical design requiring extreme care. Most of the passive electrical components available are not specified for cryogenic temperatures and should be qualified for their use. For example, capacitors fabricated with high dielectric constant material tend to change too much when cooled as well as some resistors. HEMT transistors tend to increase their gain when cooled, leading to self-oscillations in amplifiers. The optimum bias point of HEMT devices can be considerably different at ambient and cryogenic temperature. In summary, an amplifier for cryogenic operation should be specially designed, optimized and characterized for cryogenic operation.

The typical failure modes found in the field in cryogenic amplifiers are:

- Failures in solder joints, typically in connectors, induced by thermal cycles.
- Oscillations, very often out of the nominal band.
- HEMT transistor destruction by electrostatic discharges (ESD)

A considerable effort has been spent to obtain the high reliability needed in the cryogenic amplifiers needed in applications like Space Observatories (HERSCHEL mission) and low maintenance ground Radio Telescopes in remote locations (ALMA).

4.2 Example

Figure 11 shows a picture of a wideband amplifier designed to be cooled below 15 K to take full advantage of the excellent cryogenic noise performance of InP HEMT devices. Figure 12 presents the results obtained. This amplifier was designed for the IF of the ALMA band 9 receivers and covers de band from 4 to 12 GHz with an average measured noise temperature of about 6 K. The transistors are barely visible, appearing only as small dark squares in the picture.

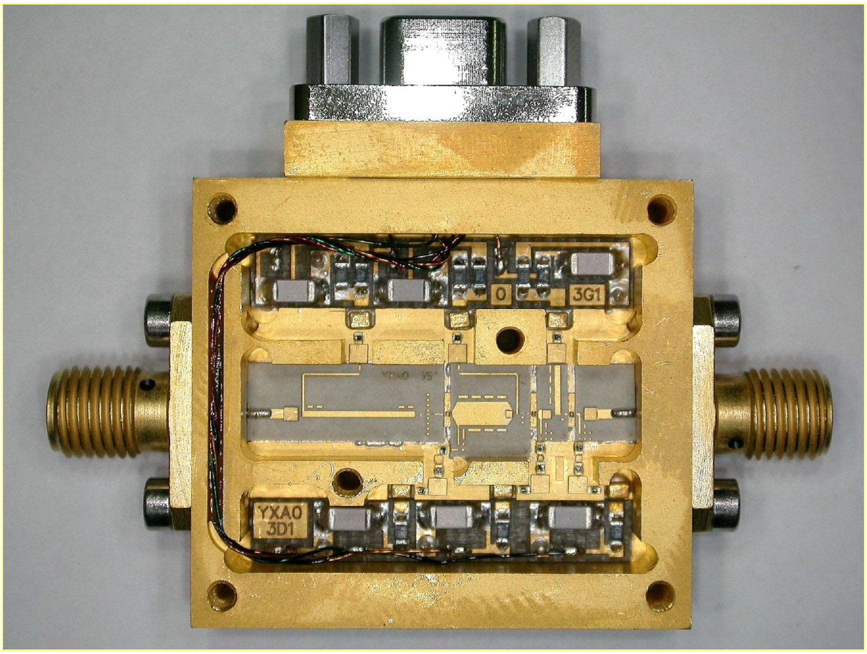

Figure 11: Photo of a 3-stage 4-12 cryogenic amplifier designed for the IF of band 9 of ALMA. Input is on the left side. Transistors are InP manufactured by HRL.

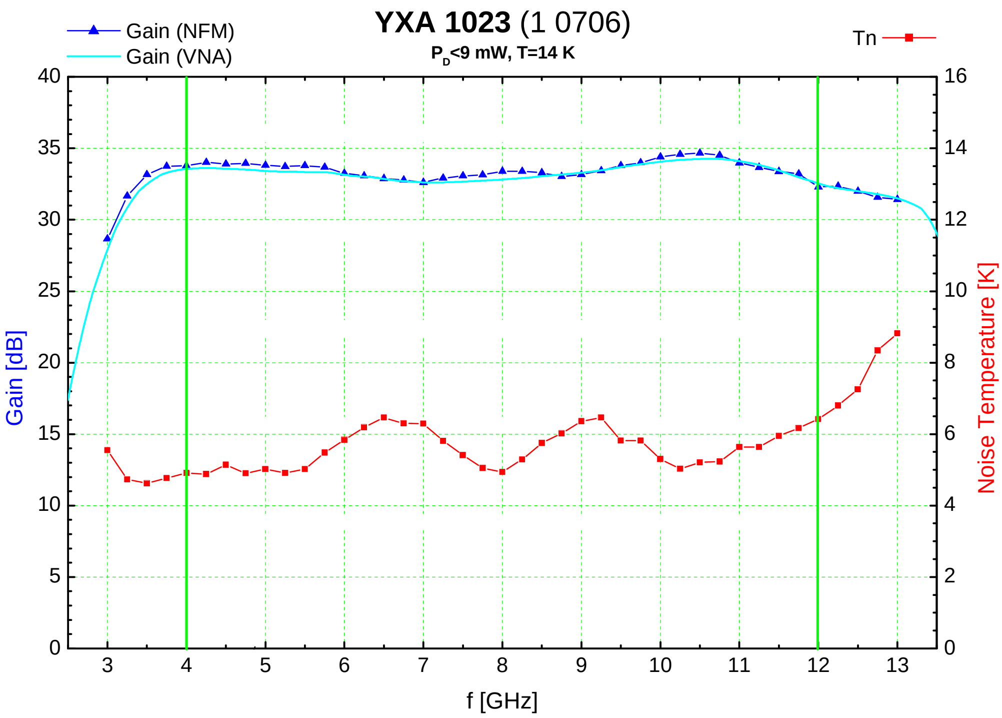

Figure 12: Plot of the measured gain (blue) and noise (red) of the 4-12 GHz amplifier cooled at 15 K physical temperature.

5. Future of amplifiers for Radio Astronomy

The technology of cryogenic amplifiers used in present generation of Radio Astronomy receivers can be considered relatively mature. Experimental InP devices have demonstrated an excellent noise performance. Unfortunately for Radio Astronomy, InP has not become a mainstream technology and GaAs dominates the commercial and military applications. The repeatability of the results of experimental devices built with InP technology is still a concern, and "hitting a god batch" is the only way to obtain the best results. While InP devices can provide excellent noise temperatures, the values obtained for gain fluctuations are not so good. The progress made in reducing the geometry of the devices has helped in reducing the noise but has made gain fluctuations even worst. In the future, the dimensions of the devices can be expected to shrink even more with the coming advances of microlithography pushed by the Si microprocessor industry.

Other possible materials to consider for the devices in future cryogenic amplifiers are metamorphic GaAs (MHEMT), heterostructures based on the InAs/AlSb interface and HBTs made of SiGe. No clear competitor of InP has appeared yet and no other technology has yet demonstrated the same level of noise performance at cryogenic temperature.

In the near future we expect to see some more development in MMICs (Monolithic Microwave Integrated Circuits), to fulfil the needs of the new generation of Focal Plane Arrays planned for present Radio Telescopes. Hopefully, this will allow building FPAs at a reasonable cost.

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