The Use of Cryogenic HEMT Amplifiers in Wide Band Radiometers

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Abstract

Advances in device fabrication, modelling and design techniques have made wide band, low noise cryogenic amplifiers available at frequencies up to 106 GHz. Microwave radiometry applications as used in radio astronomy capitalize on the low noise and large bandwidths of these amplifiers. Radiometers must be carefully designed so as to preclude sensitivity degradations caused by small, low frequency gain fluctuations inherent in these amplifiers.

1 Radiometry Fundamentals

The basic goal of microwave radiometry is to measure the total microwave power from a specified source over a defined bandwidth. The simplest radiometer consists of a low noise amplifier connected to a square-law detector. The sensitivity of such a total power radiometer is given by [l]

$$\Delta t = T_{sys}\sqrt{\frac{1}{\Delta\nu t_{int}} + \left(\frac{\Delta g}{g}\right)^2},\ \Delta t \approx 50\mu K,\ T_{sys} \approx 50K \qquad (1)$$

where At is the uncertainty of the measured microwave power (expressed in temperature units), T_{sys} is the noise temperature of the radiometer system, *Du* is the RF bandwidth of the system and t_{int} is the duration of the measurement integration. Millimeter-wave radio astronomy applications typically have values of At and T_{sys} as given in eqn(l), requiring the argument of the radical be $< 10^{-12}$. State of the art amplifiers in the mm regime [2] can achieve *Du* ≈ *l0GHz,* necessitating $t_{int} \approx$ 100sec. A problem arises due to the presence of the second term, $\frac{\Delta g}{g}$, which is the effective fractional *power* gain variation occurring during the integration interval. For a typical integration time $t_{int} \approx$ 100 seconds, fractional gain variations as small as 10^{-6} will substantially degrade performance. These gain fluctuations have a frequency dependence [3] $\frac{\Delta g}{g})^2 \propto \frac{1}{f^{\alpha}}$, $\alpha \approx 1$, allowing radiometer performance to be characterized by a knee frequency, f_{knee}, the frequency at which the two terms under the radical in eqn(1) are equal. The effect of the gain fluctuations is to limit $t_{int} \leq 1/f_{knee}$, integration periods longer than this produce little further reduction in At. Unfortunately intrinsic fluctuations of the device parameters cause such gain fluctuations, which worsen as device geometry shrinks, and upon cooling to cryogenic temperatures, both conditions required for low noise, high frequency operation.

The nature of the problem can be understood by examining the following relation for the instantaneous power incident on the detector in a total power radiometer.

$$P_{det} = (g_0 + \Delta g(t))(T_{sys} + t_{src}) \qquad (2)$$

Here the amplifier power gain is written as a sum of the mean gain g_0 and a much smaller time dependent term, $\Delta g(t)$, and t_{src} is a small signal ($t_{src} << T_{sys}$) from the source to be measured. The loss in sensitivity occurs because small $\Delta g(t)$ term multiplies the large T_{sys} term, producing large random fluctuations at the radiometer output.

Fortunately in many applications it suffices to measure *a small difference* between the microwave power from two or more sources with high sensitivity, allowing the use of differential techniques. Differential radiometers operate by employing some type of encoding which allows separation of the signal terms (those proportional to t_{src} from the noise terms (those proportional to T_{sys}) after the amplification has occurred. In a properly designed differential radiometer, the gain fluctuation term acts only on the signal corresponding to the small *difference* between the power levels of the two sources being compared. If this difference signal is much smaller than T_{sys}, the performance degradations due to the gain fluctuations can be greatly reduced.

2 Radiometer Designs

2.1 Switched Radiometers

The simplest way to implement a differential radiometer is to switch the input of a total power radiometer between two sources to be compared, and demodulate the output of the radiometer synchronously with the toggling of the input switch. [4] (fig la) The switching upconverts the input signal to higher frequencies, chosen to be above the amplifier's knee frequency. The subsequent demodulation recovers the input signal by downconverting it to DC, but rejects signals related to the lower frequency amplifier gain fluctuations. For this technique to be effective $|t_{src} - t_{ref}| \ll T_{sys}$, the magnitude of the difference signal to be measured must be small with respect to the system temperature. Non-idealities in radiometer components result in a signal at the output of the radiometer even when comparing sources at the same temperature, and is characterized by t_{offset}, the offset temperature. This too must be small compared to T_{sys}. Such designs put great demands on the performance of the switch at the input of the radiometer. The switch must have very low, stable losses and operate over wide bandwidths, often requiring the switch to operate at cryogenic temperatures. Ferrite switches have bandwidth limitations and relatively high loss, both of which greatly diminish radiometer performance. PIN diode switches also suffer from high loss. Where feasible, mechanical switches are often the best choice. For example, in a series of experiments conducted by Princeton [5, 6] (fig lb) from a site in Saskatoon. Sask. Canada., a large chopping flat was used to 'switch' the input beam of a radiometer between different locations on the sky in an experiment designed to measure the anisotropy of the cosmic microwave background radiation (CMBR) in Ka-band and Q-band. Such a switching scheme was feasible in this case since the switching frequency needed to ameliorate the gain fluctuations in this radiometer was only several Hz. The original $\approx 10\ Hz$ knee frequency of the amplifier system was reduced to below 1 mHz at the radiometer output by implementing the switching. This allowed for integration times approaching one hour to be employed to achieve the required sensitivity.

2.2 Correlation Radiometers

When the switching rate required to diminish the gain fluctuations exceeds several 10's of Hz., a correlation radiometer [l] is often the best approach. In a simple correlation receiver (fig 2) the signals from the sources to be compared are connected to two ports of a hybrid tee, say the E and H ports. The output from the colinear ports are then separately amplified and fed into a mixer which acts as a correlator. Signals presented to the input of the radiometer are split between the two legs of the radiometer by the hybrid tee and hence have a fixed relative phase between the legs. The large noise signals , T_{HEMT}, due to the noise temperature of the amplifiers are uncorrelated (apart from crosstalk in the hybrid tee) since they arise from different amplifiers. These uncorrelated signals, when applied to the two inputs of the mixer average to zero. However, the signals from the two sources, are correlated between the two legs of the radiometer and produce correlator outputs of opposite sign, since the signals originating from the E port of the hybrid are in phase when they reach the correlator and the signals from the source connected to the H-port are 180 deg out of phase at the correlator. In practice it is usually necessary to introduce another level of modulation by placing a 0/180 deg phase switch in one of the signal paths after the amplification. The output of the correlator is then demodulated synchronously with the toggling of the phase switch. This additional level of modulation is used to eliminate drifts due to non-idealities in the correlator. A variation of this approach is currently being used at Princeton in an experiment designed to detect the polarization of the CMBR at 90 GHz. In this case the input hybrid tee is replaced by an orthomode transducer with the two single polarization arms connected to the amplifier inputs, and the dual mode port observes the sky. The output of the correlator then represents the difference in power of the two linear polarizations rotated 45 degrees from the principle axis of the orthomode transducer. This radiometer has 3 channels each with $\Delta\nu \approx 3GHz$, which would have had a f_{knee} of $\approx 500\ Hz$ had a total power design been employed. The correlation design presented reduced f_{knee} to well below 20 mHz.

2.3 Hybrid Radiometers

Although correlation radiometers have excellent performance characteristics, they place very stringent requirements on the components of the radiometer. In the case of NASA's Microwave Anisotropy Probe (MAP) mission [7] cost and time constraints precluded the development of many of the components which would have been required to implement a true correlation radiometer. Under these conditions a hybrid approach was deemed best. The MAP hybrid design is similar to a true correlation radiometer, however after amplification the two signals are recombined in a second hybrid tee, the outputs of which are feed into two square law detectors, the outputs of which are then differenced. The large time varying signals, $T_{HEMT}\ .\ D\ g$, due to the noise powers of each amplifier are divided equally between the detectors and therefore appear as a common mode signals which cancel when the detector outputs are differenced. Amplified signals from the two input sources appear at opposite detectors, so the difference of the detector outputs reflects the difference in the power emitted from the sources. This approach, augmented by phase switching to remove effects related to detector gain variations, lowered f_{knee} of the outputs of the MAP W-band radiometers from ≈ 1 kHz to below 10 mHz.

2.4 Comparison with Bolometers

Radiometers based on wide band, low noise mm-wave HEMT amplifiers are beginning to rival bolometric detectors in terms of sensitivity and have several distinct advantages in terms of cooling requirements and narrow band performance. Table 1 presents a comparison of several key parameters for state-of-the-art bolometric [8, 9] and HEMT based radiometers. As can be seen in the table, bolometric systems have sensitivities comparable to or better than HEMT based radiometers, but also have much more demanding cooling requirements. The 10K operational temperature for HEMT amplifiers is readily achieved with commercially available closed cycle helium refrigerators, whereas bolometric systems require liquid cryogens which need periodically replenishment and considerable cryogenic expertise. Another advantage of HEMT systems not shown in the table is their ability to operate at ambient temperature, albeit with greatly reduced sensitivity. Room temperature operation greatly facilitates the test and verification of system integrity before beginning the somewhat lengthy process of cooling to cryogenic temperatures.

3 Conclusion

The new generation of wide band, low noise cyrogenic HFET amplifiers have led to a manyfold increase in the sensitivity of microwave radiometers. These applications however require careful radiometer designs, taking into account the small but significant departures from ideality of these amplifiers. NASA’s MAP satellite mission and ESA’s Planck mission are two such projects which require careful design to fully exploit the capabilities of these amplifiers.

References

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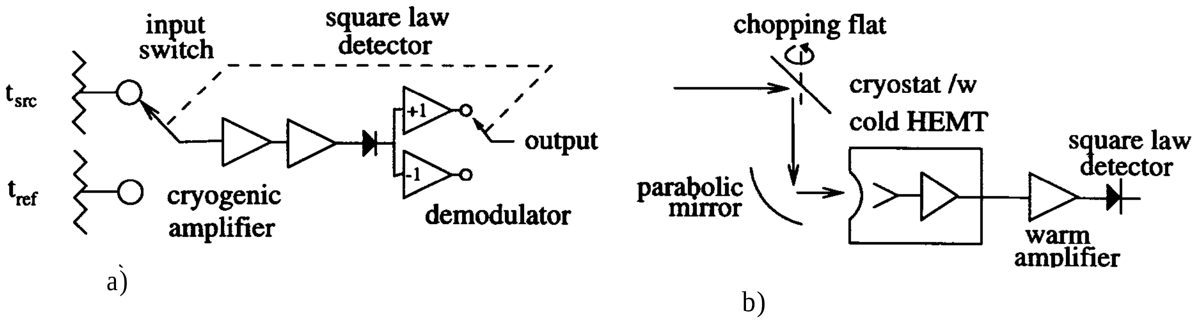

Figure 1: a) Block diagram of a switched radiometer. b) Switched radiometer as implemented in Saskatoon.

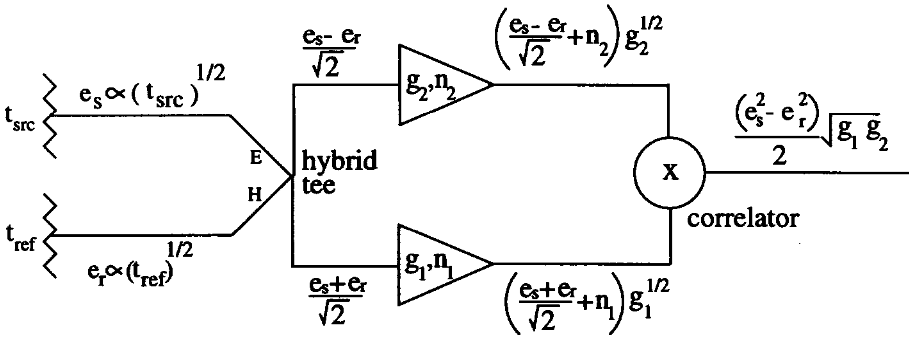

Figure 2: Bock diagram of a correlation radiometer omitting the phase switching and demodulator.

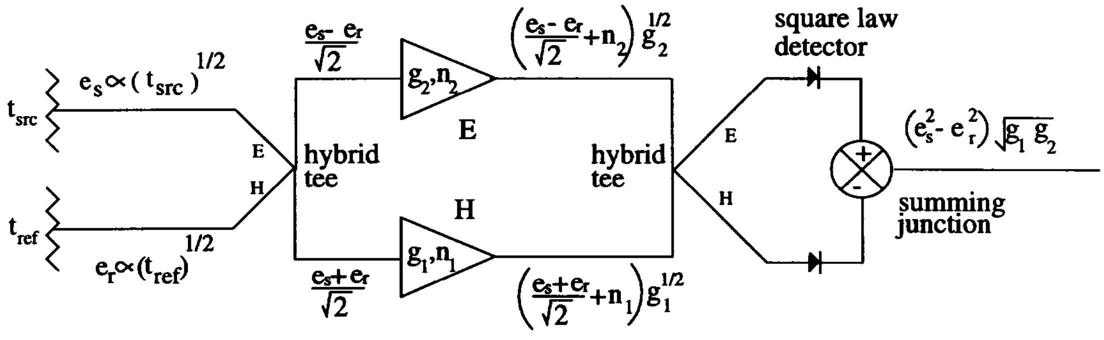

Figure 3: Block diagram of a hybrid MAP style radiometer omitting the phase switching and demodulator.

Detector	T_{phys}	Sensitivity	f_{knee}	RF frequency
MAXIMA	.1K	$150\mu K$	$\leq .3Hz$	150 GHz
Boomerang	.3K	$180\mu K$	$\leq .016Hz$	150 GHz
Boomerang	.3K	$290\mu K$	$\leq .016Hz$	100 GHz
HEMT	10K	$500\mu K$	$\leq .01Hz$	100 GHz

Table 1: Comparison of key performance parameters between HEMT and bolometric radiometer systems. Sensitivities are for a one second integration period.