380 GHz RECEIVER FRONT-END FOR THE BALLOON-BORNE RADIOASTRONOMICAL EXPERIMENT - PRONAOS -

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ABSTRACT

A submillimeter balloon-born receiver, including a 380 GHz cryogenic Schottky diode mixer, with its LO source, followed by a 6 GHz HEMT IF amplifier, has been investigated. An SIS mixer with Nb/Al-Ox/Nb junctions should increase the sensitivity by a factor 2 or 3.

I. INTRODUCTION

To prepare future radioastronomical missions aboard satellites, a submillimeter balloon-borne spectrometer is being developed under the responsibility of the french Centre National d'Etudes Spatiales. This instrument will be used to simultaneously detect the 368 GHz O_2 and the 380 GHz H_2O lines in the interstellar medium. Observations in this part of the spectrum requires low atmospheric water vapor and molecular oxygen emission, so that the 2m telescope will fly under a 900 000 m^3 balloon at an altitude of ≈ 37 km.

2. SYSTEM DESCRIPTION

To calibrate this receiver (Fig. 1), the incoming beam is commuted between a hot load and a cold load by rotation of a flat mirror. Focusing of the beam is achieved by means of elliptical mirrors, and a Mach-Zender-type diplexer is used for LO injection to the mixer. The IF is centered at 5.85 GHz to allow simultaneous detection of the two molecular lines with only one receiver, so that both sidebands of the mixer contain a signal line. IF output is fed to a cryogenically cooled HEMT amplifier, further amplified by room-temperature amplifiers and then distributed to the Acousto Optical Spectrometer subsystem. The 374 GHz LO source consist of a phase locked 93.5 GHz Gunn oscillator. followed by two multipliers.

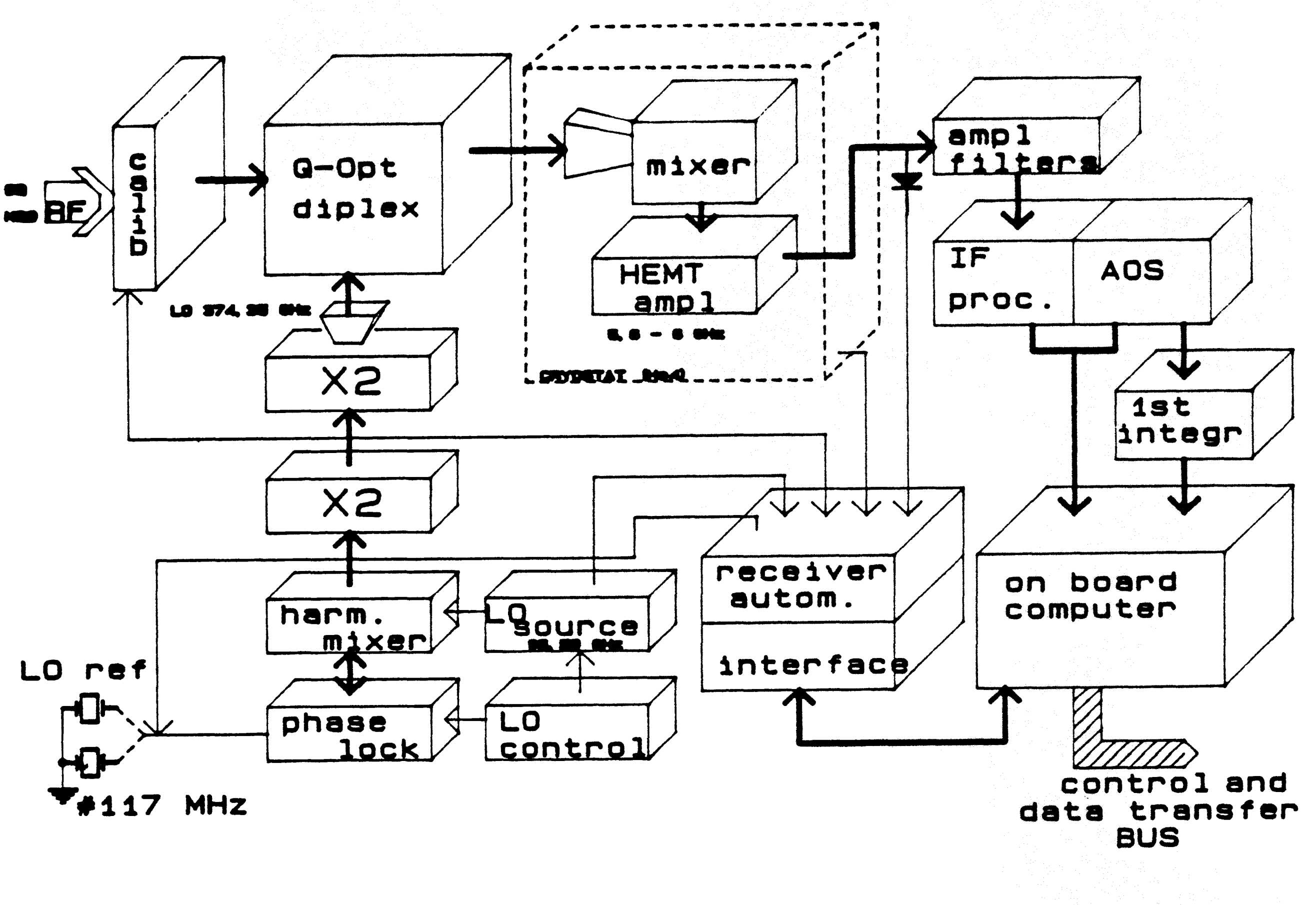


Fig 1 : In-bord recever schematic

3. SCHOTTKY MIXER DESIGN

3.1 - Diode choice

The first step in designing a submillimeter wavelength mixer is the choice of a GaAs Schottky barrier diode. The analysis given by T.W. Crowe and R.J. Mattauch[1] including time varying hot electron noise, reported receiver performance and experience of the laboratory in cryogenically cooled millimeter wavelength mixers, lead us to the choice of diodes with the following optimized parameters at 380 GHz : Cj(0) = 2.8 fF, Rs = 10 Ω at dc and Vo = $\eta kT/q$ = 29.5 mV at room temperature, and at 77 K : Rs = 29 Ω at dc and Vo = 12 mV.

3.2 - Optimum embedding impedances and driving conditions

The next task in the design procedure was to find out the optimum combination of embedding impedances seen by the diode. This was done by executing the original non-linear analysis program[2], modified to take into account time varying hot electron noise generated in the series resistance, because this noise mechanism cannot be neglected at submillimeter wavelength in an accurate mixer analysis (fig. 2). We assumed simplified embedding circuit which presents to the diode a will matched impedance at the IF port, the same impedance at both sidebands, high impedance at the second harmonic frequencies, and short-circuit at higher frequencies. This is likely to be a good approximation as it was found that sidebands beyond the second harmonic of the LO do not significantly affect the results. Moreover, with the chosen mixer mount, calculated impedances seen by the diode between 368 and 380 GHz differ by less than 10Ω, which was the accuracy of this analysis. This resulted in an optimum embedding impedance of 50 + j50Ω at both sidebands, with a 0,86 V diode bias voltage (100 μA) and a 400 μA rectified current, corresponding to a minimum mixer noise temperature, as can be seen in fig. 2. This figure also shows the effect of neglecting excess noise due to the hot electron mechanism and the correlation of its frequency components.

3.3 - Mixer mount characterization

The mixer is a single-ended fundamental waveguide mount, with a sliding finger-type contacting backshort to optimize coupling of the signals into the diode. The low value of optimum embedding impedance at sidebands lead us to choose a 0.7 x 0.12 mm reduced-height waveguide. The mixer mount includes a transition from rectangular waveguide to an integrated dual-mode Potter horn, as modified by Pickett[3], to minimize losses. The diode is contacted by a 8 μm diameter Phosphor-Bronze whisker, that has been etched. The IF is coupled out of the mixer by a section Chebychev microstrip filter, formed on a 75μm thick quartz substrate located in a 0,2 x 0,2 mm channel. This filter has been designed so that it presents a short-circuit or at least a very low impedance to the diode at the signal frequencies.

3.4 - Simplified equivalent circuit of the mixer structure

Fig. 3 illustrates a simplified equivalent circuit of the basic structure. A computer program was developed to calculate the values of Cgap and Lw from the formulae presented by R.L. Eisenhart and P.J. Khan[4]. As the whisker is bent in the practical mount, we used the approximate formula given by A.O. Lehto and A.V. Räisänen[5], which introduces a value of Lw depending upon whisker length. The low value of computed optimum embedding impedances results in a whisker as short as possible. Nevertheless, practical mount considerations lead us to use a 110 μm long whisker.

3.5 - Expected performances

The calculated impedances were then input in the mixer analysis program to find the optimum combination of mount parameter, such as whisker diameter and length, and performances of the mixer at room temperature. This resulted in the practical mount described here, with the following expected performances :

$(Tm)_{USB} = 1580$ K, $(Tm)_{LSB} = 1600$ K => $(Tm)_{DSB} = 795$ K

$(Lm)_{USB} = 7.5$ dB, $(Lm)_{LSB} = 7.5$ dB => $(Tm)_{DSB} = 4.5$ dB

$Z_{FI} = 200\ \Omega$

3.6 - RF Measurements and results

Fig. 4 illustrates the DSB mixer noise temperature and conversion loss at various LO frequencies. Tuning of the backshort was optimized at 375 GHz only, resulting in Tm = 400 K and Lm = 0.7 dB. These performances have been obtained with 150 μA diode bias, and 500 μA rectified current, a driving condition not far from the one predicted by the non-linear analysis. Less than 200 μW of LO power was required to obtain the best noise temperature, which shows that a solid-state LO can be used to pump the mixer.

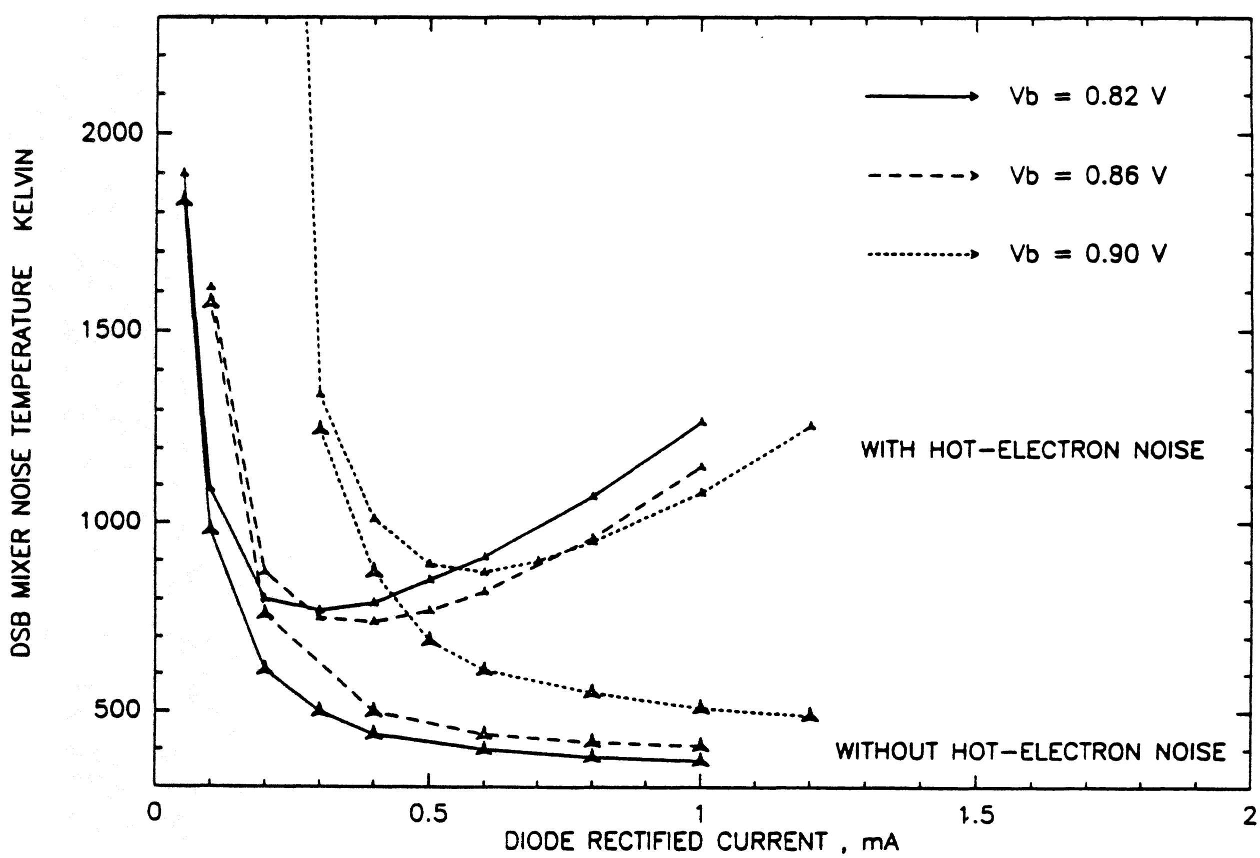


Fig. 2 : Computed minimum DSB mixer noise temperature versus P_{OL}, whith and without hot-electron noise.

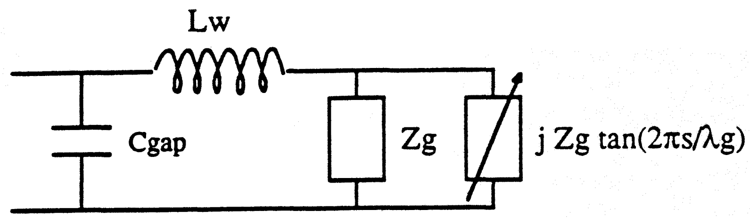


Fig. 3 : Simplified embedding network at fundamental frequency

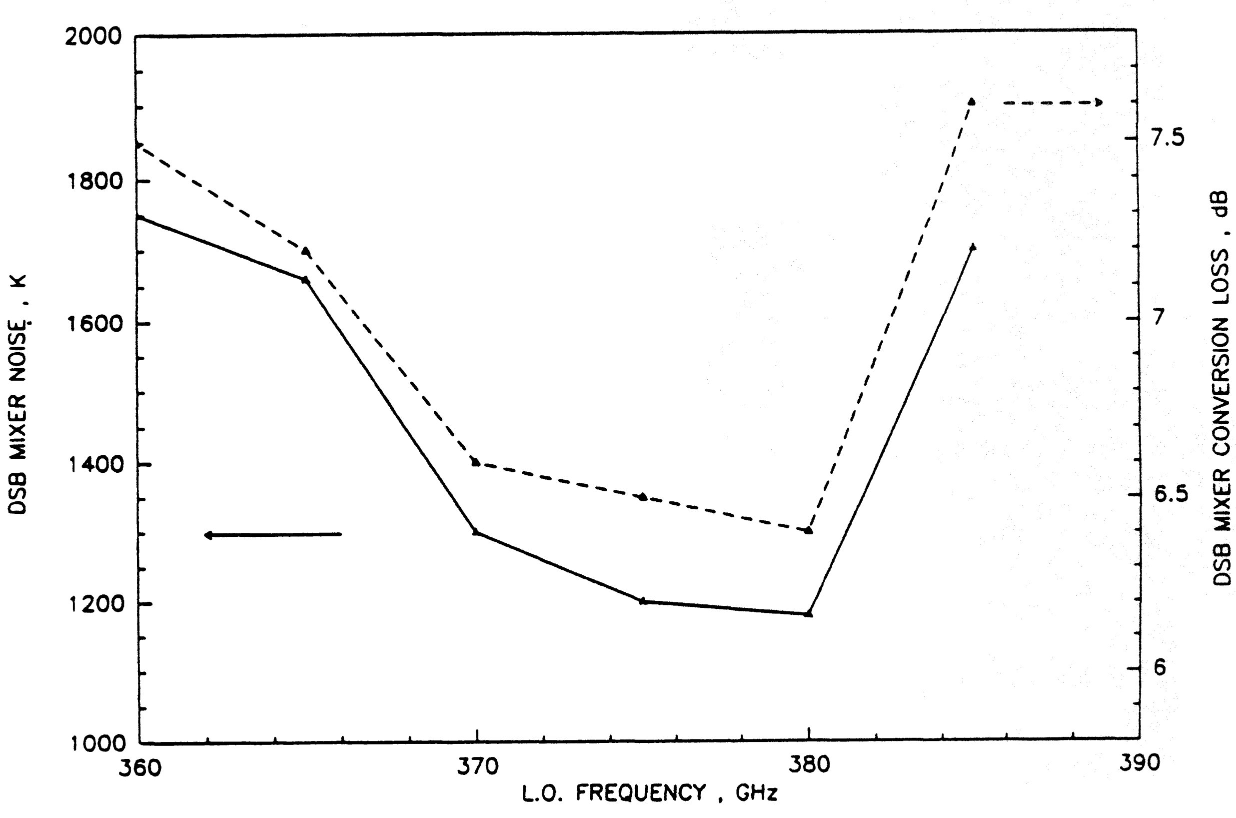


Fig. 4 : DSB mixer noise temperature and conversion loss, at various L.O. frequencies.

4. LOCAL OSCILLATOR

The 374 GHz LO source consists of a phase locked 93.5 GHz Gunn oscillator followed by two multipliers.

4.1 - Fundamental phase locked InP Gunn oscillator

Developed at the Bordeaux observatory : the fundamental InP Gunn is choice for its good performances on spectrum purity (Fig. 5a) large output power, wide band electrical tunning and reliability .

The good frequency stability≈ 10^{-8} is obtained by a classical phase-lock loop referenced to the thermaly stabilized quartz source (Fig. 5b).

Diode	Frequency (GHz)	Output power (mW)	Electrical tunning (MHz)	dF/dV (MHz/V)
Varian	93.575	40	< 200	500
Thomson	93.575	60	< 100	500
Marconi	93.575	50	> 200	600

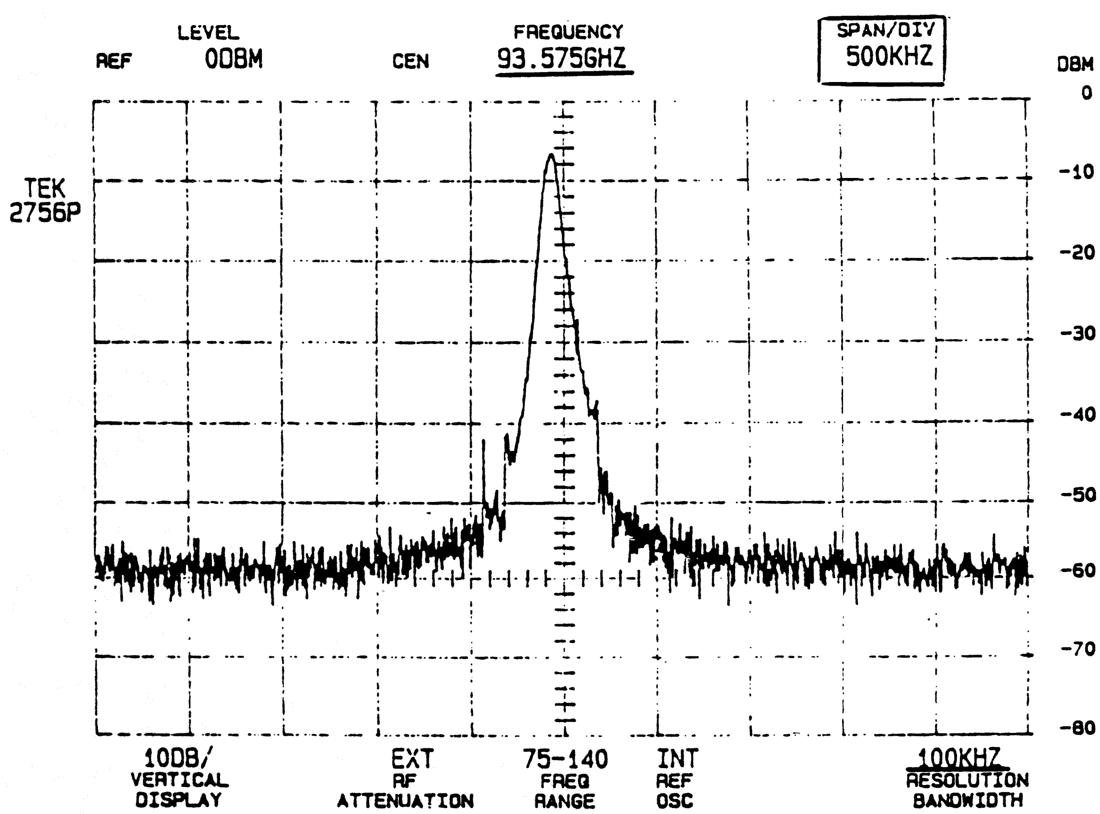


Fig. 5a : Free runing InP Gunn oscillator

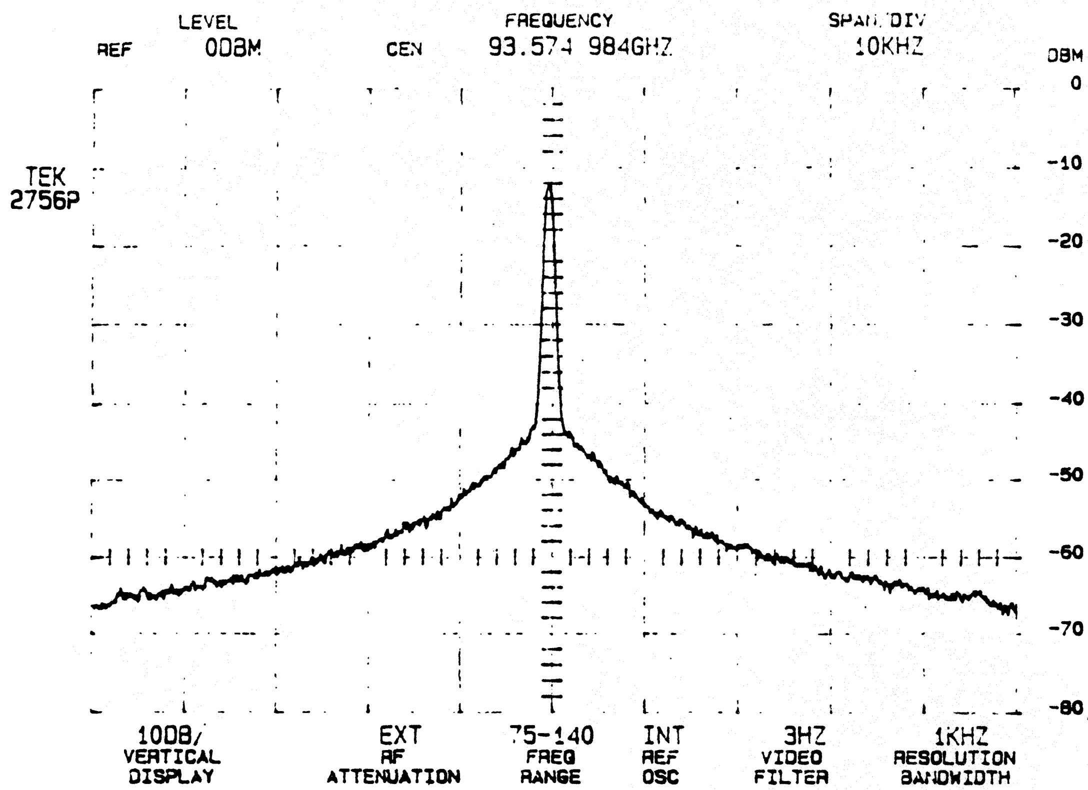
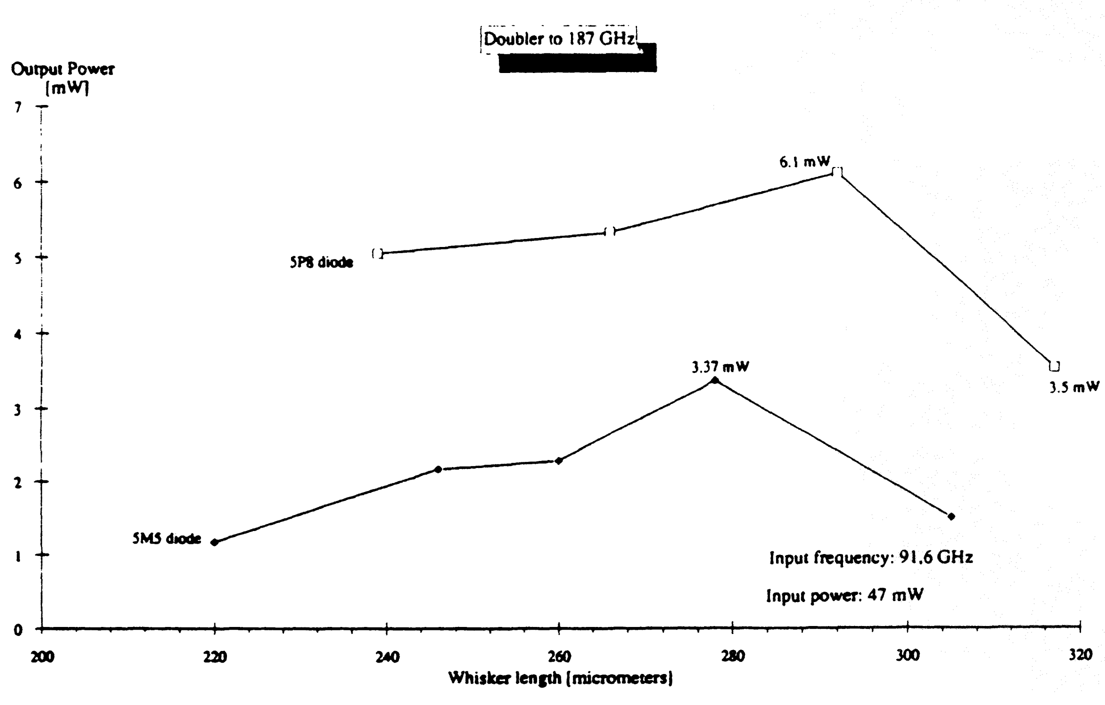


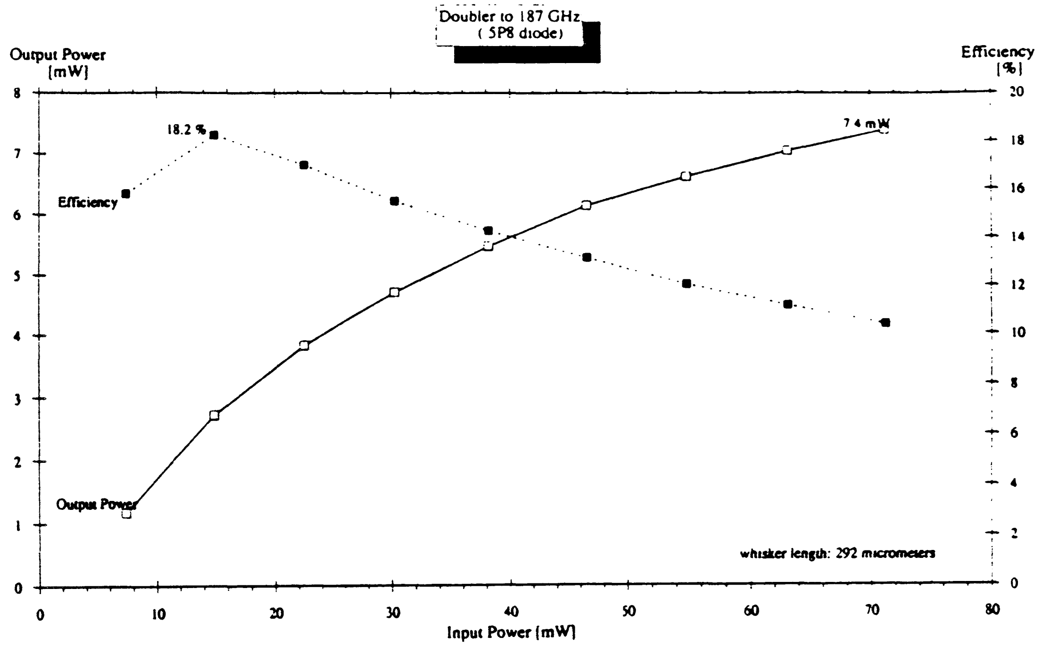
Fig. 5b : Phase-locked InP Gunn oscillator

4.2 - GaAs varactor multipliers

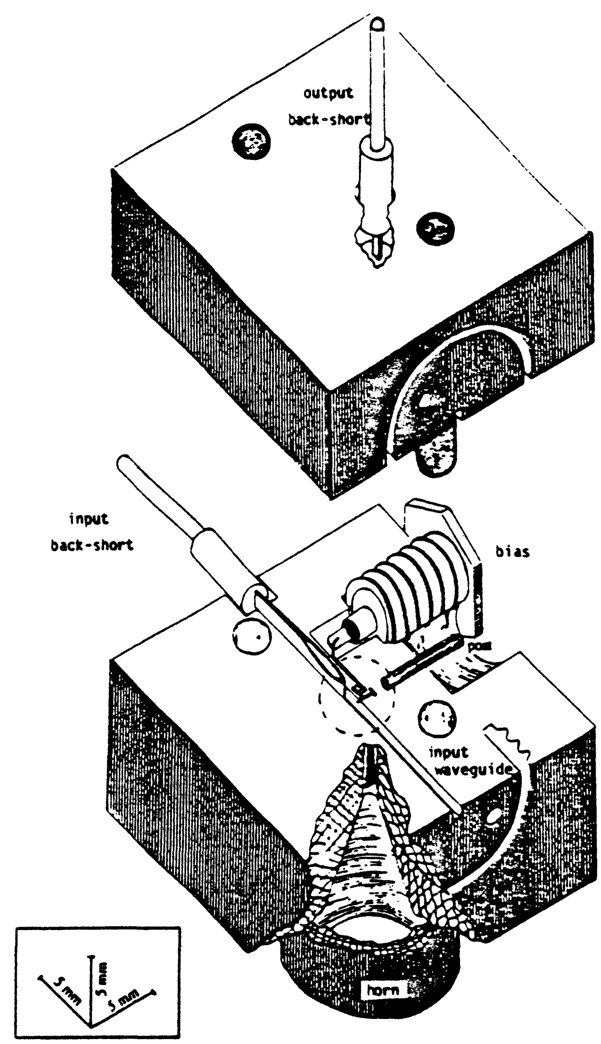
Two varactor doublers in serie are employed to obtain the LO power at 374 GHz.

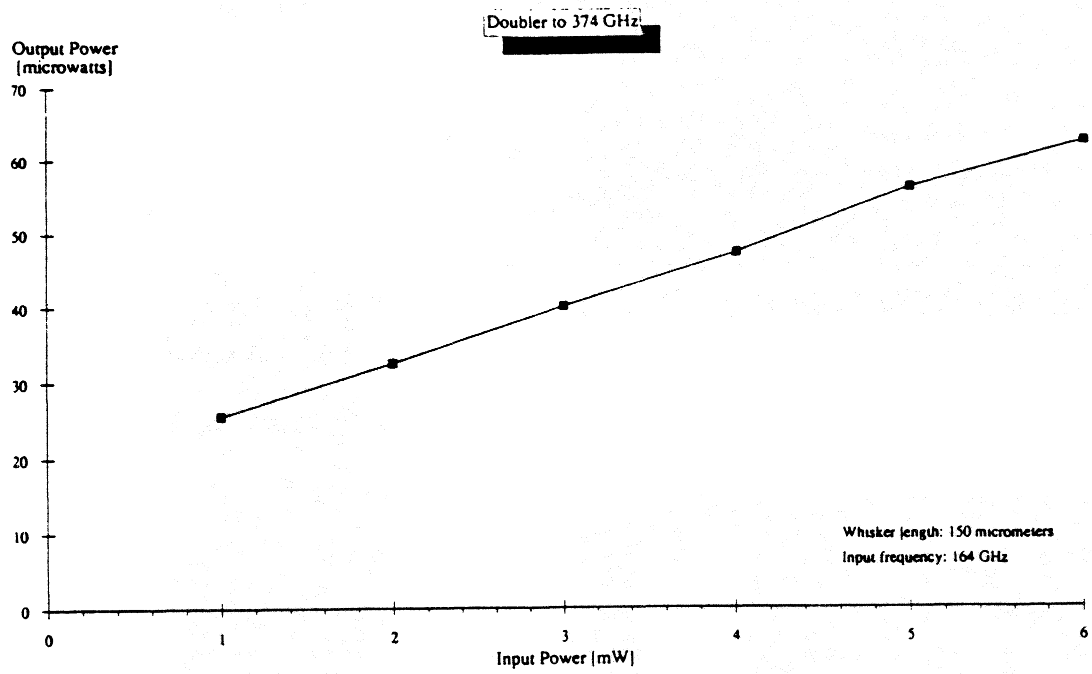
The P. Siegel design has been used to make the **first 93,5/187 GHz doubler.** Varactor diodes from U. Va are tested and good result are obtained with the 5P8 batch (Fig. 6 a et b).





The **second 187/374 GHz doubler**, designed with an integrated horn (Fig. 7a) using U. Va varactor is under tests at this moment. The output power (Fig. 7b) is not quite powerful enough to drive a Schottky mixer ; but it is enough to pump an SIS junction.





5. The 6 GHz HEMT LOW-NOISE COOLED AMPLIFIER

5.1 - Amplifier design and realization

The main aim in the design of the amplifier is to obtain a noise figure as small as possible at cryogenic temperature. Choice of transistors and of the technology of the transmission lines are two determining factors.

Amplifier gain shoud be ≥ 30 dB, so that the device includes 3 field-effect transistor stages : one HEMT (High Electron Mobility Transistor) and two conventional GaAs FET. The HEMT, which has the smallest noise figure, is at the front-end of the amplifier. After having tested several commercially available transistors, we have selected a Toshiba HEMT transistor S 8901 and two Mitsubishi FET transistors MGF 1412.

Fig. 8 illustrates the fonctional sub-assemblies of the amplifier :

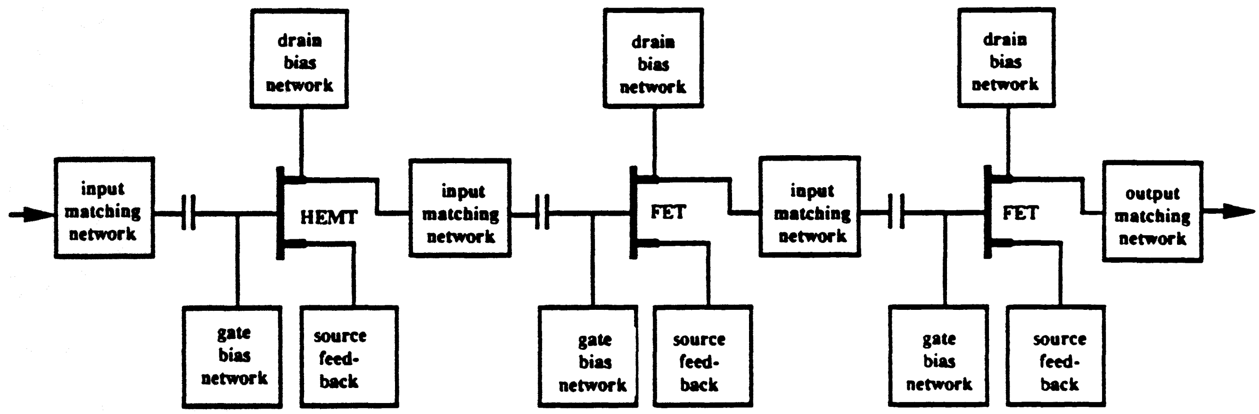


Fig. 8 : Synoptic scheme of the amplifier

The generator impedance of the transistor should be specified in order to obtain minimum noise. This optimum noise impedance is achieved by computer-aided matching lines[7]. The technology of coaxial line is chosen for its better performances at cryogenic temperatures. Indeed, it is based on the assembly of components which tolerates small contractions when the device is cooled down, thus avoiding to damage the bondings.

Matching networks mainly consist of quarter wave transformers, tunable on transmission lines[8]. Thus accurate tuning can offset the differences between transistors. Bias networks include conventional d.c. block, by-pass elements and Zener diodes to protect the transistors against surges. Source feed-backs allow low input reflexion simultaneously with the lowest noise ; they consist of a small source inductance whose connection to ground can be adjusted[9].

5.2 - Measurements and results

An important part of the study was devoted to the determination of the optimum operating temperature. In flight, the amplifier is located on a thermal screen, whose conduction with the "4K stage" of a liquid helium increases as the amplifier temperature decreases. Thus, it is necessary to know the variation of the amplifier noise temperature as a function of the physical temperature, in order to choose the optimum screen temperature.

Gain and noise curves are presented in fig. 9 at room and cold temperatures. At a 27 K physical temperature, noise temperature is less than 21 K and gain flatness is $\pm$ 0.7 dB over the required bandwidth (5.6 - 6.1 GHz). The minimum noise temperature is 16K.

With the VSWR values ($\leq$ 1.5 at input and $\leq$ 1.3 at output), the use of our isolator is avoided. A small microstrip circuit has been realized to allow impedance matching between mixer output and amplifier input.

Noise temperature variation during the cooling is shown in Fig. 10. At the present time, we have chosen an operational temperature of 40 K as a trade-off between the weight of the cryostat and performances of the amplifier.

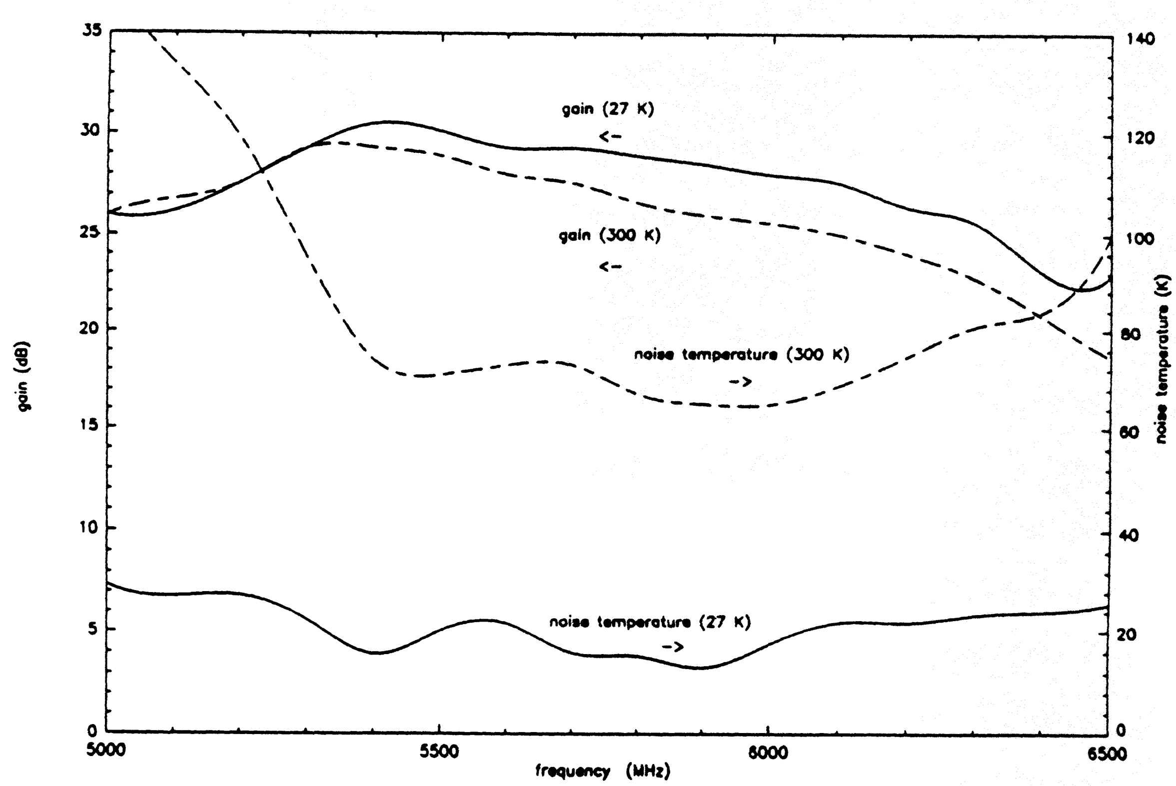


Fig. 9 : Measured characteristics of the amplifier

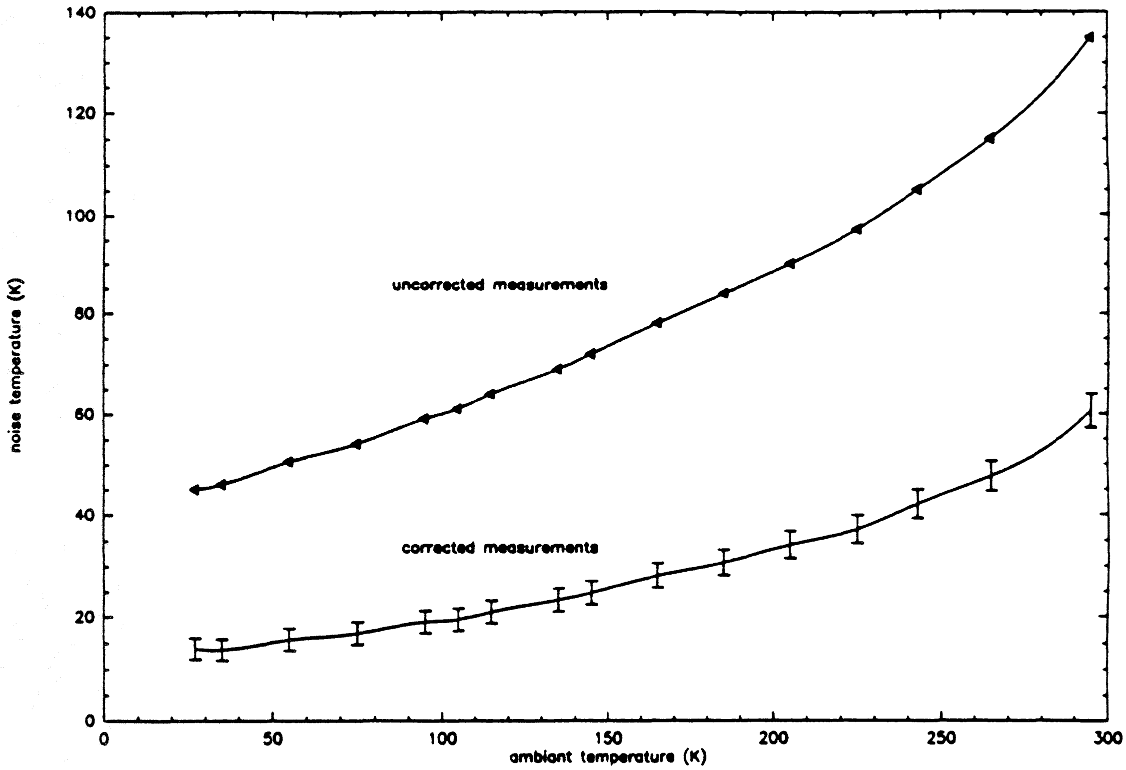


Fig. 10 : Noise temperature function of physical temperature

6. SIS Nb/Al-Ox/Nb JUNCTIONS

6.1 - Introduction

Difficulties in generating enough Local Oscillator (L.O.) power at high frequencies make SIS mixers very desirable for operation above 300 GHz. Their low LO power requirements and their low noise temperature are pushing many radioastronomy groups to develop SIS receivers in this frequency domain. While lead junctions have been widely used up to 760 GHz[10] their performance degrades with time which makes them especially difficult to use for space applications. Junctions made with a niobium or any niobium alloy film are mechanically very hard and very stable with respect to storage at room temperature and repeated thermal cyclings : we call them "all-refractory junctions". These characteristics have led these components to be used for very high speed integrated circuit technology[11,12].

The fabrication of rugged junctions using refractory materials like Nb/Al-Ox/Nb or NbN/MgOx/NbN is actively pursued by different groups as an alternative solution :

the specific properties of these types of junctions are very suitable for use in heterodyne receivers.

6.2 - Fabrication process of the tunnel junctions

We report the successful fabrication of small (2μm^2) arrays of Nb/Al-Ox/Nb junctions with excellent I/V characteristics resulting in low-noise receiver performance measured in the 80 - 115 GHz frequency range[19]. To obtain SIS mixers working at high frequencies (100 - 500 GHz), very small Nb/Al-Ox/Nb junctions (area $\leq 2\ \mu m^2$) are required. We have developed a fabrication process at the Ecole Normale Supérieure (Paris) with the collaboration of the Centre d'Etudes Nucléaires de Saclay (DPh-SRM, Ormes des merisiers) . Our process is based on "selective Niobium Etching Process (SNEP) first developed by Gurvitch et al [13,14] and improved by Yuda et al [15]. The main points are :

- deposition of the NB/Al-Ox/Nb sandwich without breaking the vacuun in order to obtain a good metal barrier interface.
- self-alignement insulation process in order to fabricate small junctions.
- definition of the junction area by Reactive Ion Etching (RIE).

The differents steps of this process are described on Fig. 11.

For radioastronomy applications, it is necessary to use fused quartz substrates $\leq 100\ \mu m$ thick) and to deposit stress-free films to obtain junction areas under 4 μm[16,17]. We succeeded in realizing all Niobium junctions down to 4 μm^2 (Fig. 12). Contrary to lead junction fabrication processes, our method leads to a high rate of successful junctions made on a single wafer (about 70%) with similar characteristics (josephson current, normal resistance). For operation at 100 GHz, we fabricated an array of 4 tunnel junctions in series which corresponded to an effective area of 1 μm^2. The I/V characteristic is shown in Fig. 13. The normal resistance R_N of this array is 206 Ω. The sharpness of this curve is excellent : the leakage current is below 2 μA at 4.2 K and unmeasurable at 2.5 K with this sensitivy. Moreover, this characteristic did not change over six months at room temperature.

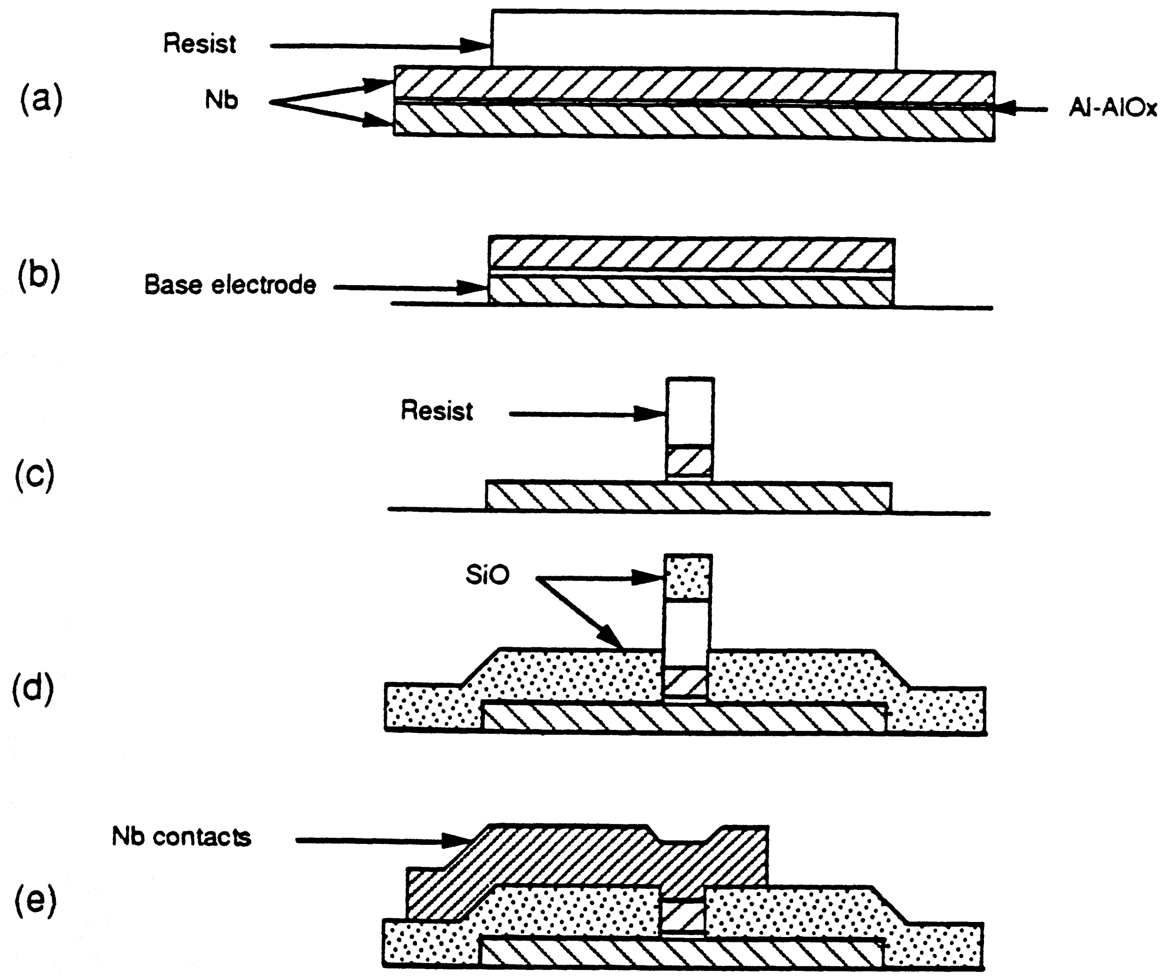


Fig. 11 : Fabrication process of NB/Al-AlOx/Nb junctions (a) Nb/Al-AlOx/Nb deposition. Definition of the base electrode by photolithography. (b) Trilayer etching. (c) Upper electrode etching. (d) self aligned depostion of a SIO insulating layer. (e) Nb interconnection layer.

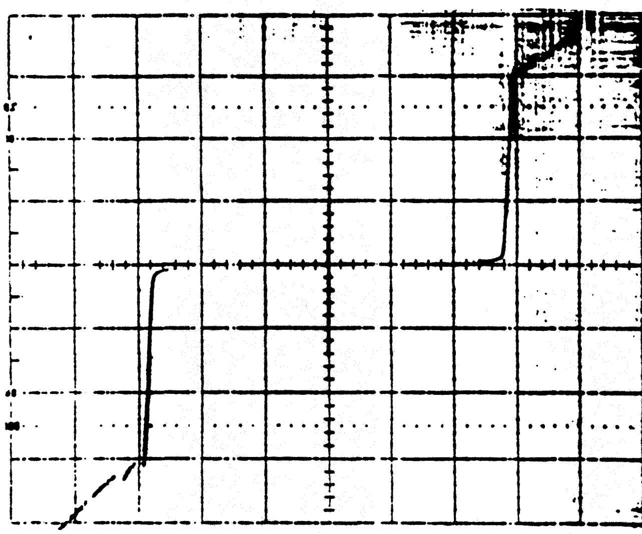


Fig. 12 : TRI 38 # 3

$S_{eff} = 2\mu m^2$; $R_N = 103\ \Omega$;

$R_{300K} = 140\ \Omega$

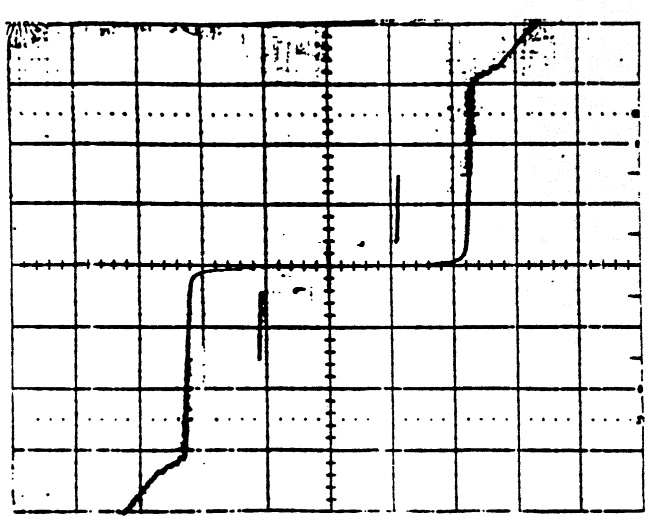


Fig. 13 : TRI 38 # 1

$S_{eff} = 1\mu m^2$; $R_N = 206\ \Omega$;

$R_{300K} = 230\ \Omega$

The "knee" structure after the gap voltage is a consequence of a proximity effect[18]. This effect can be reduced by decreasing the aluminium thickness of the trilayer. We note that the Josephson currents of the two junctions in series are equal within the measurement uncertainties. This criterion is fundamental for mixer applications.

The 2 μm square junctions are very stable to repeated thermal cyclings between room and liquid He temperature. This is an important improvement compared with lead-alloy junctions.

7. CONCLUSIONS

A 380 GHz Schottky diode mixer was analysed theoretically, designed, constructed and tested over à 25 GHz bandwidth. time varying hot-electron noise has been taken into account, resulting in a more accurate analysis. Theoretical simulation showed that is may be possible to obtain 4.5 dB DSB conversion loss, and 800 K mixer noise temperature. However, these performances require reduced bandwidth and lossless waveguide mount, which is far from a pratical mount at 380 GHz. Experimentally, we obtained minimum conversion loss and noise : Lm = 6.5 dB and Tm = 1200 K, at 375-380 GHz. The main reason to the difference between theoretical and experimental results may be losses of the waveguide mount, as 1.8 dB surface resistance losses lead to almost the same performances. The rest of the difference can be explained with slightly different diode parameters, and excess noise due to the use of a carcinotron as the LO, or overlooked mechanisms such as intervalley scattering and trap induced noise[6]. The next step will be to cool the mixer down to cryogenic temperature. However, these first experimental results confirm the possibility of using such a mixer in a submillimeter balloon-born spectrometer for radioastronomical observations.

The 374 GHz phase-locked LO source has been made with an InP fundamental Gunn oscillator at 93,5 GHz followed by two GaAs varactor doublers. This subsystem is under tests but it gives enough power to drive an SIS mixer.

An HEMT IF amplifier has been specifically designed for cryogenic applications, it meets fully the specifications and will be used in connexion with a submillimeter mixer. The contribution of the amplifier to the system noise is about 20%. Next improvements is to smooth the gain and noise curves over the band of interest.

SIS Nb/Al-Ox/Nb junctions with small areas have been sucessfully fabricated, implemented and characterized in a receiver system working in the 3 mm wave frequency range[19]. A very important fact is that the Nb junctions proved very stable with repeated thermal cyclings betwen room and liquide He temperature. This is an important improvement compared to Pb junctions. The Nb/Al-Ox/Nb junctions do constitute a very promising mixing element for space applications. Many improvements on the fabrication process are in view in order to reach 1 μm^2per junction and to operate up to 400 GHz for the balloon borne experiment : study of etching profiles, utilization of an electron beam lithography, and development of other fabrication processes.

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