A Wideband Fixed-Tuned SIS Receiver For 200 GHz Operation

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Abstract

We report on the design and development of a heterodyne receiver, designed to cover the frequency range 176 GHz to 256 GHz. This receiver incorporates a niobium superconductor-insulator-superconductor (SIS) tunnel junction mixer, which, chiefly for reasons of reliability and ease of operation, is a fixed-tuned waveguide design. On-chip tuning is provided to resonate out the junction's parasitic capacitance and produce a good match to the waveguide circuit.

Laboratory measurements on the first test receiver indicate that the required input bandwidth (40%) is achieved with an average receiver noise temperature of below 40 K. Mixer conversion gain is observed at some frequencies, and the lowest measured receiver noise is less than 30 K. Furthermore, the SIS mixer used in this receiver is of simple construction, is easy to assemble and is therefore a good candidate for duplication.

I. Introduction

The first radio astronomy observations of the millimeter-wave molecular transitions of CO and CN were made in 1970 [1,2]. Since that time, millimeter-wave radio astronomy has evolved considerably: numerous millimeter-wave observatories are now in routine operation and receiver technology has reached a high degree of maturity [3]. At submillimeter wavelengths this is not the case. There are only two specially designed ground based submillimeter-wave observatories in routine operation: the Caltech Submillimeter Observatory and the James Clerk Maxwell Telescope. A number of other submillimeter-wave observatories are being developed (e.g., the Submillimeter Telescope, a joint project between the University of Arizona and the Max Planck Institut für Radioastronomie), or are under construction (e.g., the Antarctic Submillimeter Telescope Remote Observatory).

The Submillimeter Array (SMA), currently under construction at the Smithsonian Astrophysical Observatory, will be the first submillimeter-wave synthesis telescope. Consisting of six 6-meter antennas, each to be equipped with eight SIS receivers designed to operate throughout the major atmospheric windows from below 200 GHz to above 900 GHz, the SMA will benefit from the rapid evolution of Nb SIS mixer technology.

II. Mixer Design

Given that many SIS receivers currently operate in the 1.3 mm atmospheric window [3], the lowest frequency unit appears to be the easiest of the SMA receivers to design. However, a number of factors render its design more difficult. For example, operating at its lowest frequency, with an intermediate frequency (IF) of 5 GHz, the signal to IF ratio is only a factor of 30, compared to about 100, typical of most working SIS receivers. Extra care is therefore required in the design of on-chip mixer tuning so as not to inadvertantly short out part of the IF signal. Also, since the interferometer will operate at a remote high altitude site, where mechanical tuning of the mixer circuit is excluded, a fixed-tuned design with an instantaneous input bandwidth of about 40% is required.

Current technology dictates the choice of a waveguide based mixer with corrugated feed for high efficiency operation. The large instantaneous signal bandwidth is most readily achieved using an inductively compensated SIS junction. The mixer mount is therefore chosen to present a real impedance at the junction feed point across the signal input band. Furthermore, since the mixer output is reasonably coupled to the 50 Ω IF amplifier network by using a junction with normal state resistance of about 20 Ω, a low mount impedance is required. A low mount impedance is also required to ease the design constraints of the thin-film tuner. Following standard design procedures and using experience gained with SIS mixers operating at similar wavelengths, a scale model mixer mount was made in reduced height waveguide. The dimensions of the waveguide and suspended substrate filter design were selected so as to produce a 35 Ω real impedance at the junction feed point, located at the center of the symmetrical low-pass filter structure. This impedance is transformed via an integrated thin-film microstrip circuit fabricated with the SIS junction to achieve the required signal coupling at the junction.

A block diagram of the mixer circuit is given in Figure 1a. The substrate carrying the junction and filtering structure is sandwiched between the corrugated waveguide horn feed and a back-section containing a short length of waveguide. The low-pass filter design is shown in Figure 1b; the substrate is suspended with the metalization facing the corrugated horn feed. The length of the mixer back-section and the dimensions of the first element of the filter that deliver the desired impedance at the feed point have been determined from the scale model measurements. The measured feed point impedance is shown in Figure 1b. Measurements were made over the frequency range 4.4 GHz - 6.4 GHz, and indicate that an instantaneous signal bandwidth of about 40% is possible with this design.

III. Junction Tuning and Fabrication

In order to achieve wideband operation an ωCR product of 2.3 (at 200 GHz) was chosen. For a reasonable match to the IF port, a normal state resistance of 17 Ω was used as a design goal. This implies the use of trilayer material with a current density of 7500 $A.cm^{-2}$ for a nominal junction area of 1.5 μm^2. The corresponding optimum source conductance was deduced from an empirical formula [4].

An integrated series inductive line and a two section impedance transformer, similar to that previously described [5], were used to match the optimum source conductance in parallel with the junction geometrical capacitance to the 35 Ω feed point impedance provided by the waveguide mount. The design of the matching network was performed with the help of Touchstone, taking the kinetic inductance of the superconducting strips into account, and is shown schematically in Figure 2. Also shown in the Figure is the calculated return loss for this arrangement as a function of signal frequency. Clearly, a reasonably good match, better than 10 dB, is possible over the required signal input bandwidth of 80 GHz.

The SIS junctions used in this receiver were made using optical lithographic techniques similar to those described in the literature [6]. In order to allow for some parameter variation during fabrication, three junction sizes were made, each with the same on-chip tuning circuit.

IV. Receiver Performance

The SMA receiver package will consist of eight receivers, housed in a common cryostat and cooled using a closed-cycle helium refrigerator. For receiver noise measurements in the laboratory, however, it is more convenient to use a small liquid helium filled test dewar. Receiver noise measurements are made using the Y-factor method with room-temperature (295 K) and liquid nitrogen (77 K) cooled loads. Since the mixer has a wide signal input bandwidth, all receiver noise data should be considered double-side-band and are obtained with the mixer at 4.2 K. A beamsplitter, presenting low-loss in the signal path, is used to combine signal and LO input to the mixer. The signals then pass through a laminated plastic vacuum window [7], a cooled porous Teflon window [8], and a Teflon lens, cooled to 4.2 K, before entering the mixer feed horn. We should note that no corrections are made to our data for losses in front of the receiver.

The measured receiver noise as a function of local oscillator (LO) frequency for a number of different mixers is displayed in Figure 3. For all these measurements, the IF amplifier network has a center frequency of 1.5 GHz, an instantaneous bandwidth of 500 MHz and a noise temperature of about 5 K. From the Figure, the mixer incorporating the SIS junction with an area of 1.3 μm^2 and a normal resistance of 22.5 Ω, i.e. that closest to the nominal design (1.5 μm^2 and 17 Ω respectively), offers excellent low-noise performance over a band that is centered slightly lower than the design frequency, by about 3%. In an effort to push the operating band upwards, the same type of junction was used in a mixer whose back-section was shorter than that determined by scale model measurements, by about 60 μm. In this case, the center frequency of the receiving band was increased by about 3%, i.e. to the desired value, with little change in average receiver noise. A junction with area 1.1 μm^2 and normal resistance 27.5 Ω was then tested in the original mixer. In this case, the receiver noise floor increased by about 5 K and the receiving band center remained unchanged. Clearly, any of the configurations tested offer performance, both in bandwidth and in noise, that will enable the SMA to start operations with state-of-the-art receivers. Furthermore, testing of a number of similar mixers indicates that the performance shown is readily achievable.

Standard measurement techniques [9,10,11] have been used to separate the receiver noise into three components: noise due to input losses, mixer noise, and multiplied IF noise. Figure 4 shows the breakdown of noise for the receiver incorporating the small area SIS junction mixer. With mixer noise close to the quantum limit at these frequencies, a total receiver noise of about 30 K should be considered as a good design goal, with about equal noise arising from input losses, mixer noise and multiplied IF noise. From the Figure we observe that, while the individual sources of noise contribute about equally at some frequencies, there is room for some improvement at low frequencies through the use of lower-loss input optics. We also note that the mixer noise is relatively high at the center of the receiving band, and that some small reduction in noise may be possible as lower noise IF amplifiers become available.

In Figure 5 we present current-voltage characteristics and IF output power curves for four different LO frequencies. The Figure indicates that excellent mixer conversion is obtained at 230 GHz, good conversion at 180 GHz and 205 GHz and poorer conversion at 255 GHz. We should note that only the LO frequency and drive level were changed beteween the different receiver noise measurements, all other parameters were fixed. In particular, the mixer bias and magnetic field were held constant. This demonstrates that good receiver performance is readily achievable. Optimization of receiver noise at all frequencies may require fine adjustment of all parameters. However, since only a few K reduction in receiver noise is achieved, it is thought that further optimization may not be justified.

Finally, in Figure 6, we show the receiver noise performance as a function of LO frequency for different IF amplifier networks. Two sets of data are presented in the Figure, one for an IF 500 MHz wide, centered at 1.5 GHz, the other for an IF 2.5 GHz wide, centered at 5 GHz — the IF of the SMA. Since the mixer gain is close to unity over a large part of the receiver's operating frequency, the difference in receiver noise is approximately equal to that of the difference in IF amplifier noise, i.e. about 7 K. The lowest measured receiver noise is about 25 K for the 1.5 GHz IF and 30 K for the 5 GHz IF. From the Figure, the receiver noise averaged over an 80 GHz input bandwidth is about 30 K for the 1.5 GHz IF and below 40 K for the 5 GHz IF.

V. Conclusion

We have developed a wideband, fixed-tuned SIS receiver for 200 GHz operation. The receiver noise is below 40 K across the majority of the observing band, about 80 GHz wide. Although some improvement may be possible through the use of lower-loss input optics and IF amplifiers offering superior noise performance to those currently available, it is thought that the current receiver design, which is particularly well adapted to duplication, will prevail and offer state-of-the-art performance when the SMA begins operations in 1997.

Acknowledgement

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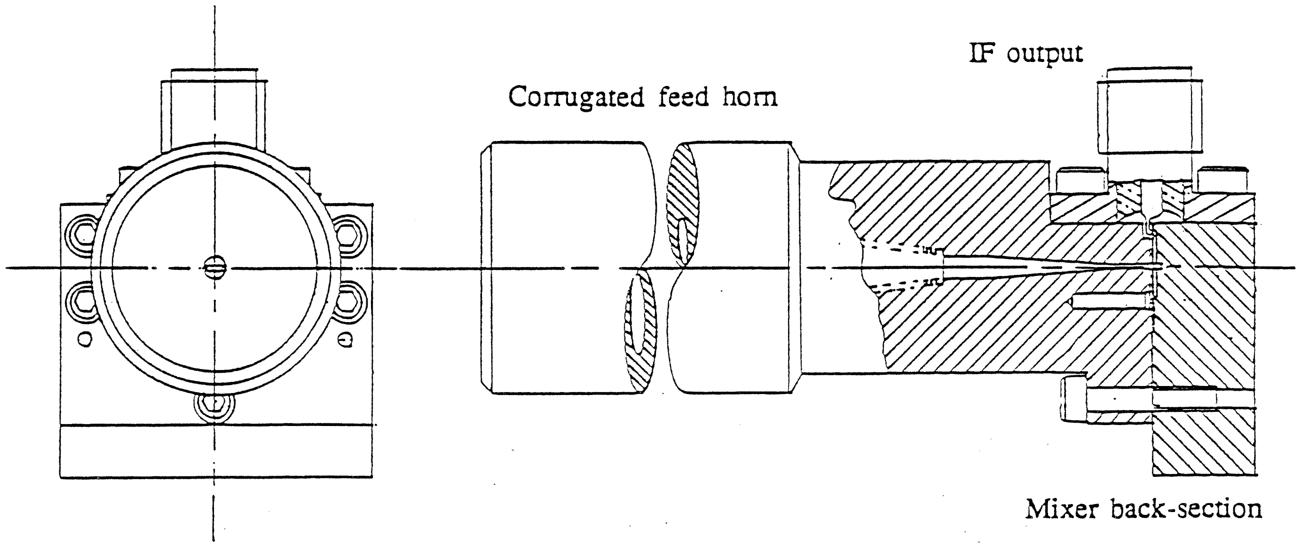

Figure 1a. Mixer mount detail showing the corrugated horn feed and mixer back-section.

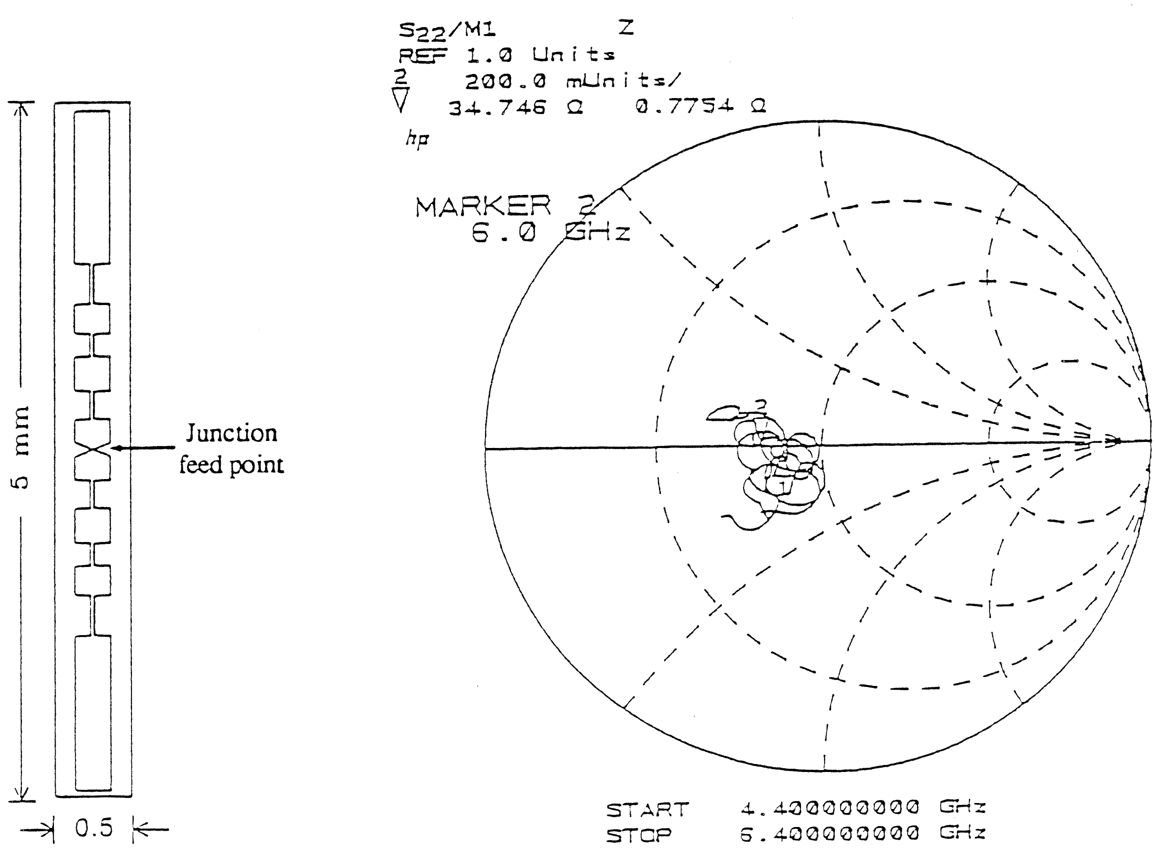

Figure 1b. Suspended substrate filter layout, and the locus of the junction feed point impedance.

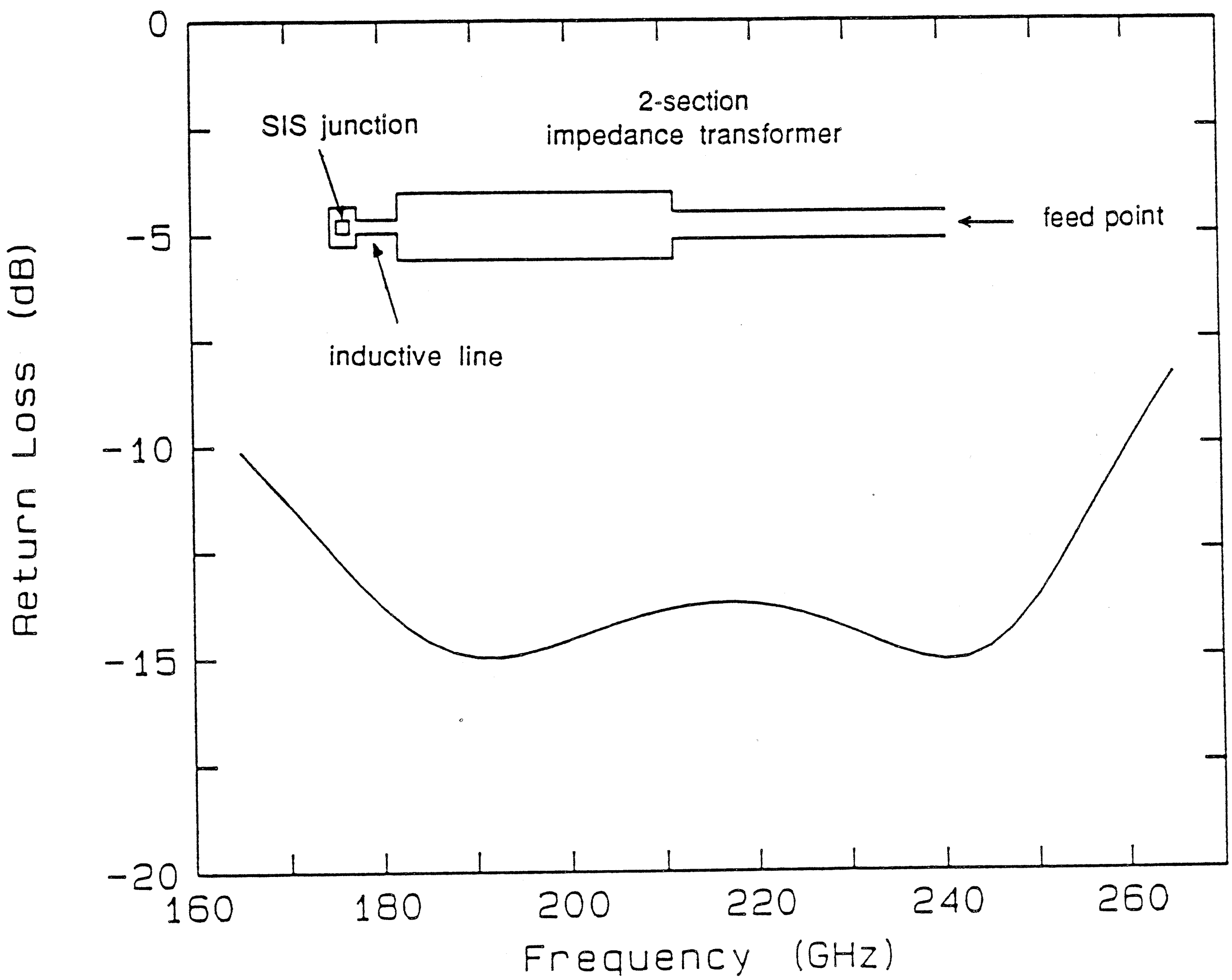

Figure 2. Layout of the integrated microstripline tuning structure showing the SIS junction, the inductive line and the two step impedance transformer.
Also shown is the calculated return loss across the signal frequency band.

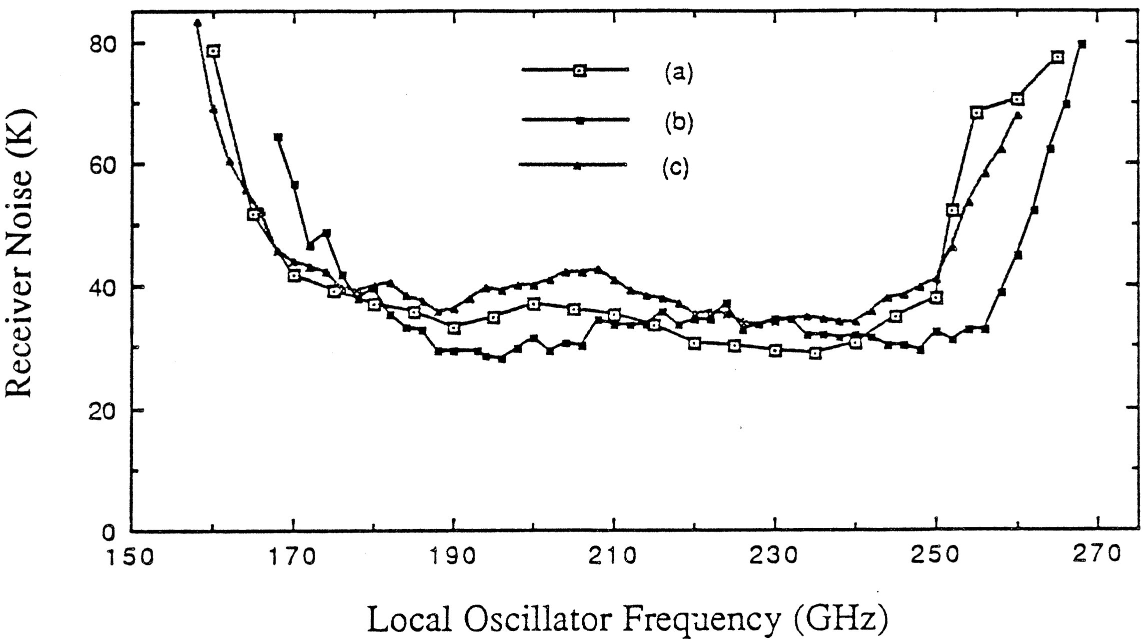

Figure 3. The receiver noise is plotted as a function of LO frequency for three mixer configurations:

(a) 1.3 square micron junction in a mixer with the standard length back-section,
(b) 1.3 square micron junction in a mixer with reduced length back-section,
(c) 1.1 square micron junction in a mixer with the standard length back-section.

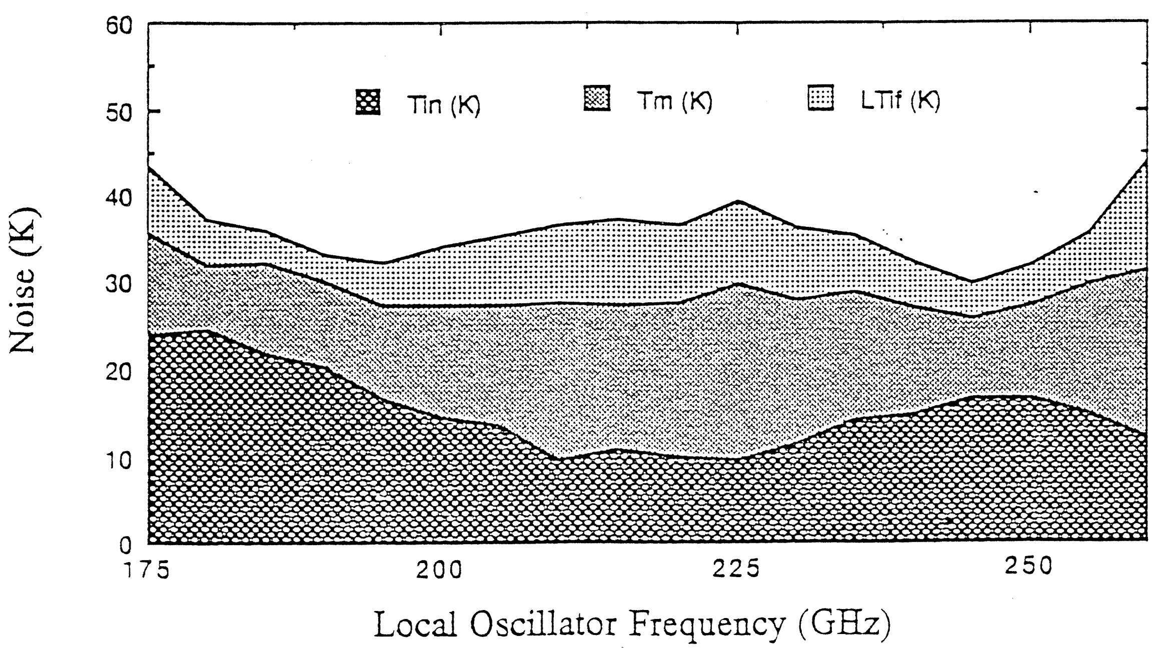

Figure 4. A breakdown of receiver noise into its three components: input loss noise, Tin (K), mixer noise, Tm (K), and multiplied IF noise, LTif (K) is plotted as a function of LO frequency.

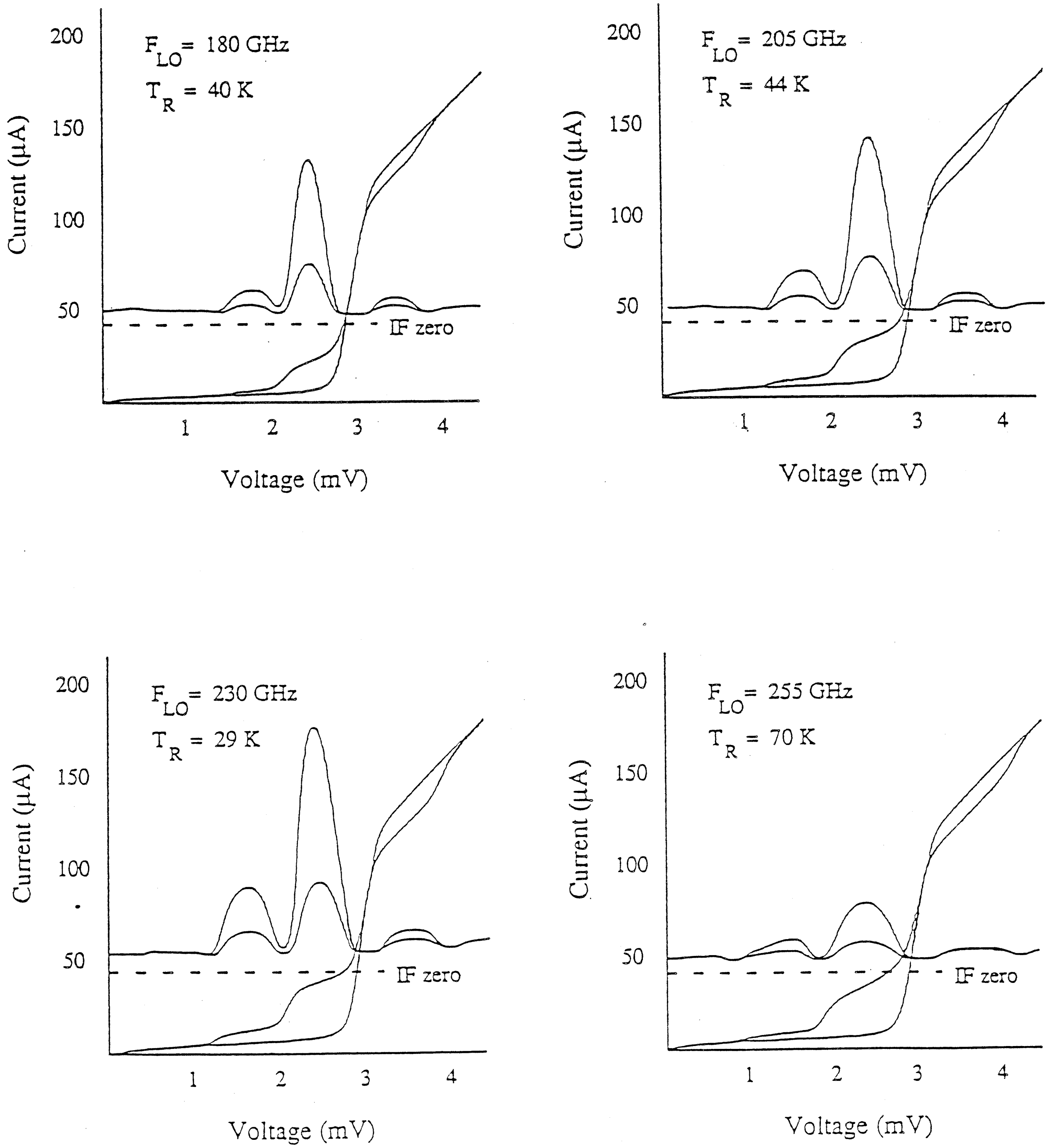

Figure 5. Current-voltage characteristics, pumped and unpumped, are given for four different LO frequencies. Also shown is the receiver output in response to hot (295 K) and cold (77 K) input loads.

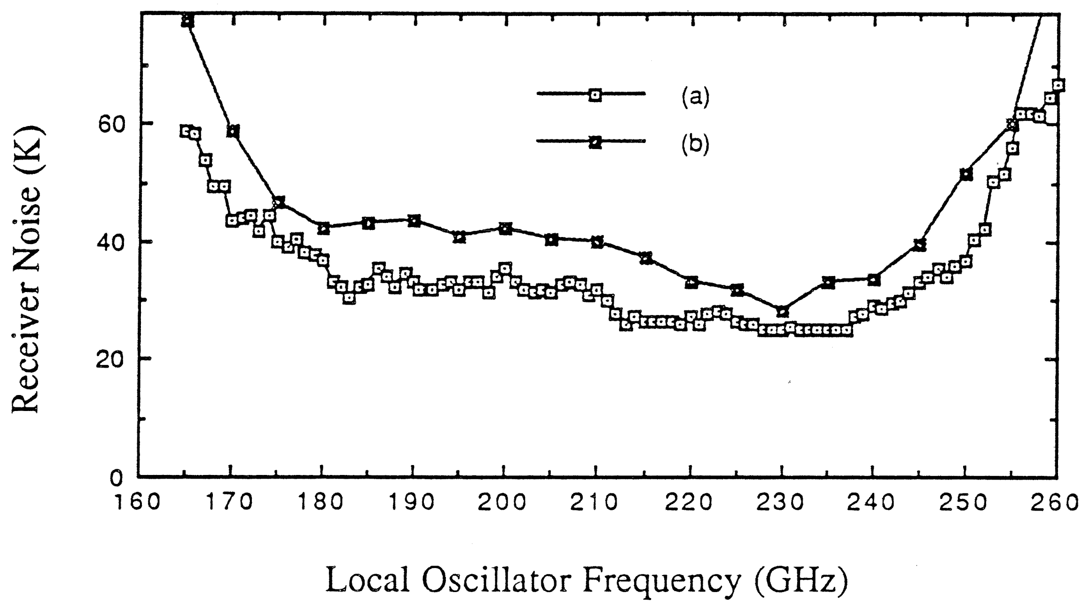

Figure 6. The receiver noise is plotted as a function of LO frequency for two different IFs:
(a) 1.5 GHz center frequency, 0.5 GHz bandwidth.
(b) 5 GHz cnter frequency, 2.5 GHz bandwidth