A Low Noise NbTiN-based 850 GHz SIS Receiver for the Caltech Submillimeter Observatory

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Abstract

We have developed a niobium titanium nitride (NbTiN) based superconductor- insulator-superconductor (SIS) receiver to cover the 350 micron atmospheric window. This frequency band lies entirely above the energy gap of niobium (700 GHz), a commonly used SIS superconductor. The instrument uses an open structure twin-slot SIS mixer that consists of two Nb/AlN/NbTiN tunnel junctions, NbTiN thin-film microstrip tuning elements, and a NbTiN ground plane. The optical configuration is very similar to the 850 GHz waveguide receiver that was installed at the Caltech Submillimeter Observatory (CSO) in 1997. To minimize front-end loss, we employed reflecting optics and a cooled beamsplitter at 4 K. The instrument has an uncorrected receiver noise temperature of 205K DSB at 800 GHz and 410K DSB at 900 GHz. The degradation in receiver sensitivity with frequency is primarily due to an increase in the mixer conversion loss, which is attributed to the mismatch between the SIS junction and the twin-slot antenna impedance. The overall system performance has been confirmed through its use at the telescope to detect a wealth of new spectroscopic lines.

Keywords

SIS receiver, twin-slot planar antenna, NbTiN superconductor, bandgap energy, AlN tunnel barrier, RF loss, and cooled optics.

I. INTRODUCTION

In 1997 a waveguide receiver[1] covering the 350-micron atmospheric window was deployed at the CSO. It used a novel 1 μm thick Silicon Nitride membrane which support an all niobium based Superconductor-Insulator-Superconductor (SIS) junction. With an uncorrected receiver sensitivity of 500 K DSB at 810 GHz, it was state of the art at that time. The performance of this receiver was limited however by a large absorption loss in the niobium superconductor films. This loss arises because the mixer is operated above the energy gap of niobium (690 GHz). In this regime, photons have enough energy to break Cooper pairs in the superconductor films resulting in a large RF loss and poor mixer conversion gain. An alternative to the use of niobium superconducting transmission lines is the use of normal metals such as gold (Au) or Aluminum (Al)[2][3]. However, it is required that any metals employed will have to be compatible with the SIS fabrication process. Even though pure Au and Al conductivity improves by a factor of 5-10 when cooled to 4 K, these metals exhibit a high loss when compared to an ideal superconductor, such as niobium[7]. Above 800 GHz the loss of Au/Al transmission lines becomes less than that of niobium ($\approx$ 40 % loss per wavelength), but even so the use of a higher bandgap energy superconductor is much preferred. To minimize loss in front of the waveguide mixer, we designed the optics with mirrors and beamsplitter cooled to 4K where possible. This scheme gave us a total front-end loss of $\sim$ 1.1 dB, and an overall mixer conversion gain of - 12.3 dB at 822 GHz. Of the 12.3 dB conversion loss, about 4dB was due to the actual mixing process, 0.4 dB due to the RF mismatch, and the remaining 6.8 dB due to the niobium film loss! Clearly much was to be gained if the niobium loss could be reduced or even eliminated. And so, even as the 850 GHz waveguide receiver was commissioned at the telescope in 1997, it had become very clear that improved mixer sensitivity would result if a higher bandgap (2Δ) superconductor could be found. Fortunately such a development was underway at JPL in order to facilitate SIS receivers up to 1200 GHz for both ESA/NASA FIRST[4] satellite mission and NASA/SOFIA airborne observatory[5]. At that time we reported[6][7] on the first RF test results of NbTiN films used in combination with Nb and NbTiN tunnel junctions. Three combinations had been tested up to 650 GHz, namely:

- NbTiN ground plane with Nb wiring and a Nb/Al-O_x/Nb tunnel junction
- NbTiN ground plane with Nb wiring and a NbTiN/MgO/NbTiN tunnel junction
- NbTiN ground plane with Nb wiring and a Nb/Al-N_x/NbTiN tunnel junction

The first such combination rendered a receiver noise temperature of 110K at 639 GHz, the second combination resulted in a receiver noise temperature of 250K at 638 GHz, and finally the Nb/Al-N_x/NbTiN devices yielded a receiver noise temperature of 195K at 588 GHz. These heterodyne measurements, as well as extensive direct detection measurements with a Fourier Transform Spectrometer (FTS), indicated the NbTiN surface loss to be less than 0.1 Ω/square at 600 GHz. Even the NbTiN/MgO/NbTiN SIS junction results were the best ever recorded and gave credence to the low loss RF properties of NbTiN. Though no heterodyne response had been measured above the niobium superconducting gap (700 GHz) at that time, resonances in the dc IV-curves were observed up to 1 THz on certain devices. These as well as many unreported FTS measurements during the course of 1997 yielded valuable information about NbTiN superconducting films and AlN barrier properties. Finally by April 1998 we were ready for another mask design.

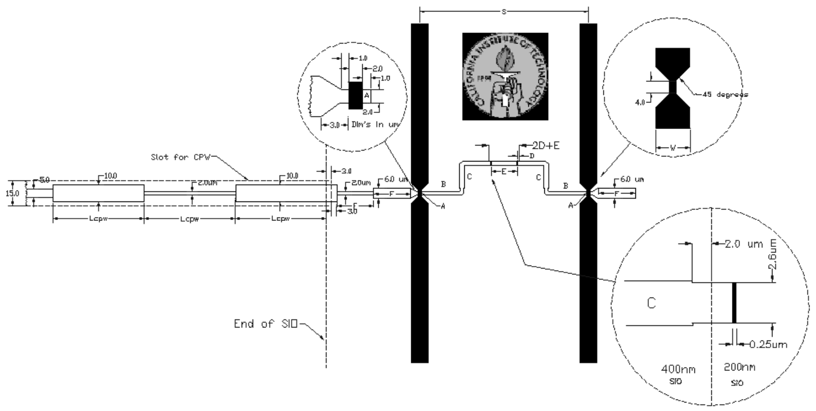

Fig. 1. NbTiN mask design, April 1998.

II. Twin-Slot Mixer Mask Design

Comparative studies of computer simulations and FTS direct detection laboratory measurements provided us with the necessary device properties needed for a new mask design. These properties are summarized in Table I. The layout was designed to maximize the number of possible combinations of Nb, NbTiN, Au, and Al wire & ground planes with AlO_x and AlN_x tunnel barriers. AlN_x being the more compatible barrier for the NbTiN deposition process[8][9]. The design was done for 550 GHz, 650GHz, 850GHz, and 1050 GHz.

The three features of the design that are worth noting are the open-ended microstrip line termination of the slot antenna, the CPW IF output and dc bias line, and the introduction of "long" sub-micron e-beam junctions. First, the traditional radial stub termination[11] was replaced by a much lower capacitance $\lambda/4$ open-ended microstrip line for the purpose of reducing the capacitive load seen at the IF port of the mixer. Second, the IF line was implemented in CPW rather than microstrip for the same reason. The driving motivation for these changes is the eventual need to increase the intermediate (IF) frequency of the mixer from the present 1-2 GHz to 4-8 GHz. This is done in order to better facilitate future

TABLE I

Device parameters used in the April 1998 mask design

Parameter	**Range**
R_nA / Junction	20 Ω-μm^2
Junction Area	0.25 μm x 2.6μm
Wiring Thickness	250 nm
Ground Plane Thickness	300 nm
NbTiN Properties	$\rho = 80 \mu\Omega$–cm
	$\lambda = 230$ nm
	T$_c$= 15.3 K
Nb Properties	$\rho = 5 \mu\Omega$–cm
	$\lambda = 80$ nm
	T$_c$= 9.2 K
Specific Capacitance AlN$_x$	85 fF/μm^2
Specific Capacitance AlO$_x$	85 fF/μm^2

extragalactic astronomical observations[4][5].

The results presented in this paper are with a 1-2 GHz IF, however developments are underway to upgrade to a 4-8 GHz bandwidth within the next few years. Thirdly, FTS data seems to indicate the possible effect of kinetic inductance, which is a quantum mechanical effect caused by RF currents crowding into the SIS junction[10]. The effect of kinetic inductance can be better understood by considering how the twin-slot mixer[12][13] tuning circuit works. The twin-slot antennas generate a voltage that is 180 degrees out of phase due to symmetry. Because of this there is a virtual ground in the center of the tuning structure (Fig. 1), and the junction capacitance is cleverly tuned out by the shunt inductance of the microstrip line connecting the two junctions (E/2). At the very high frequencies, the tuning inductor (E/2) becomes smaller and smaller and any kinetic inductance presented by the SIS junctions becomes proportionally more significant. To circumvent this problem, we introduced "long" e-beam submicron junctions in our design. Much effort has gone in mak-

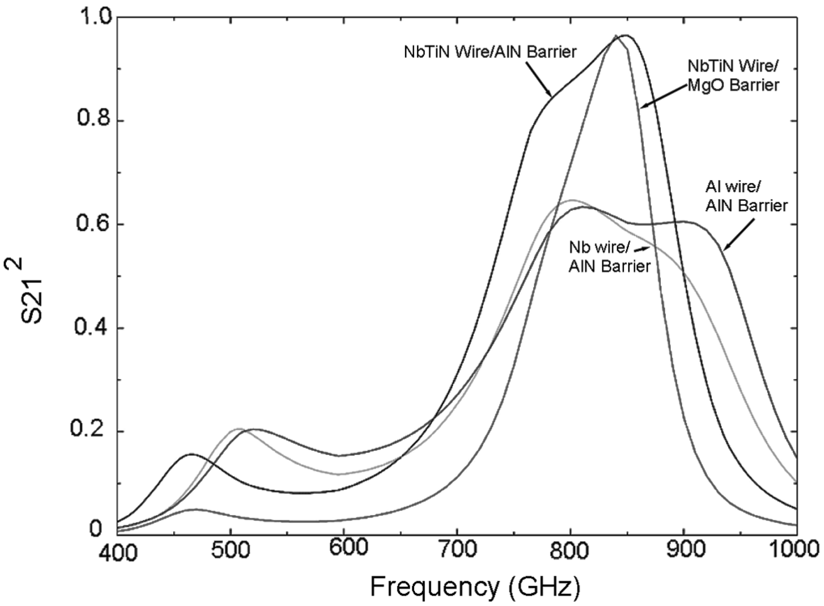

Fig. 2. Circuit Simulations of 4 different style SIS junction and tuning structure configurations. In all cases the ground plane is NbTiN. Design was optimized for 850 GHz.

ing these devices, and as a consequence the fabrication process at JPL has matured considerably in the last few years. The results presented in this paper are produced by "long" sub- micron Nb/AlN$_x$/NbTiN hybrid tunnel junctions with a NbTiN ground plane and wire layer.

The details of the fabrication process, the FTS measurement results, and actual device parameters are described in more detail in a recent publication by Kawamura[14] *et.al.* The junctions we used for this work have a critical current density of 10 kA/cm^2 and are of reasonably high quality with a sub-gap to Rn ratio of $\sim$ 15 (measured at 2 mV). Being a hybrid junction, the gap was expected to be at 4 mV (ΔNb + ΔNbTiN), however the actual measured gap voltage was about 3.2 mV. The most plausible explanation is that the NbTiN counter electrode in the vicinity of the barrier is of poor quality. The April 1998 mask incorporates a NbTiN ground-plane and works with 4 different SIS junction configurations (Fig. 2); a NbTiN/AlN$_x$/NbTiN tunnel junction with a NbTiN wire layer, which is the mixer under discussion in this paper; a NbTiN/MgO/NbTiN junction with NbTiN wiring; a NbTiN/AlN$_x$/NbTiN junction with an Al wire layer, and a NbTiN/AlN$_x$/NbTiN junction with an Au wire layer. The specific capacitance of AlO$_x$ and AlN$_x$ are very similar, $\sim$ 85 fF/μm^2 for a 10kA/cm^2 current density junction. The specific capacitance of MgO on the other hand is much larger, $\sim$ 145 fF/μm^2 for a 10kA/cm^2 current density device. The latter junction capacitance is much more difficult to tune out, which is evident from Fig. 2. The RF bandwidth of the NbTiN/AlN$_x$/NbTiN tunnel junction with NbTiN wire layer & ground plane is about 130 GHz, which agrees well with the measured heterodyne response presented in Fig. 8.

III. Cooled Optics

The noise temperature of a receiver is not only dependent on the conversion gain of the mixer, but also on loss in the front-end optics. In the case of the 850 GHz waveguide receiver[1] we tried to maximize the optics throughput by carefully selecting the IR blocking filters, 300K pressure window, and by eliminating the use of plastic lenses. Furthermore, to minimize the absorption loss contribution from the 19 μm reflective mylar beam splitter, we decided to combine the RF and local oscillator (LO) power on the LHe stage. Fig. 3 shows an isometric view of the optics configuration. The waveguide mixer shown has been replaced with the twin-slot NbTiN SIS mixer under discussion. The infrared and atmospheric pressure windows of the cryostat consist of anti-reflection coated quartz disks. The twin-slot mixer described by Zmuidzinas[11][12] *et. al.* is depicted in Fig. 4. The mixer consists of a twin-slot planar feed antenna connected to a pair of SIS junctions via a microstrip transmission line (Fig. 1). A hyperhemispherical silicon lens and plano-convex teflon lens are used to focus the incident radiation onto the antenna. The

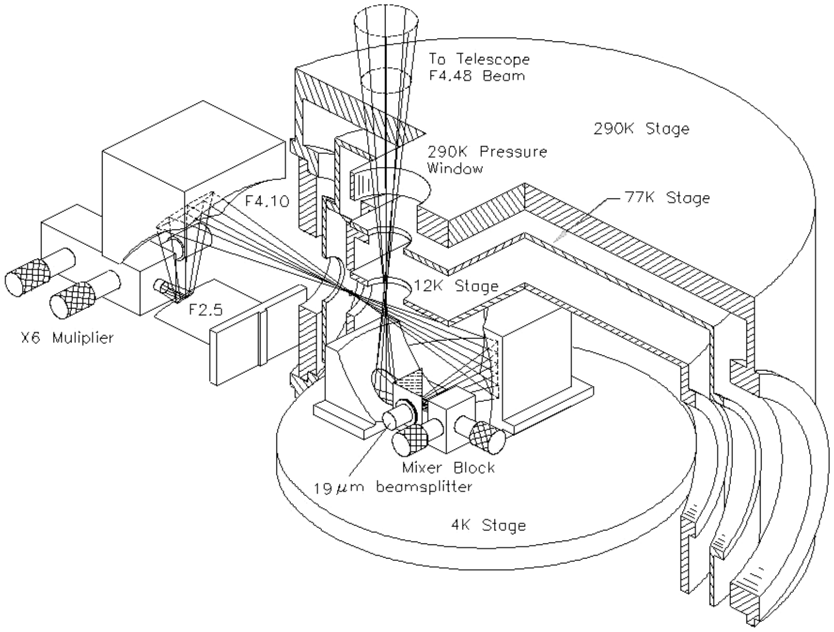

Fig. 3. Isometric view of the cooled optics configuration used in the 850 GHz waveguide receiver. The cryostat is mounted upside down in the Cassegrain focus of the Caltech Submillimeter Observatory.

silicon lens has a diameter of 12.7 mm (0.500 inches) and has a virtual focus ≈ 30 mm behind the planar twin-slot antenna.

In order to upgrade the niobium based waveguide receiver (Fig. 3) with a NbTiN based twin-slot mixer, and at the same time utilize as much of the existing hardware as possible, two significant changes had to happen. First, the plano-convex teflon lens needed to be removed. And secondly, once this lens was removed, the virtual focus had to be moved much closer to the backside of the hyperhemispherical silicon lens because of the now fast (F/2.5) mixer beam. These changes in effect called for a complete re-design of the twin-slot mixer optics. The reasons for the removal of the plano-convex lens in Fig. 4. can be summarized as follows.

The mixer beam, using reciprocity, has to come to a focus at the F/4.48 Cassegrain focus of the telescope which is located

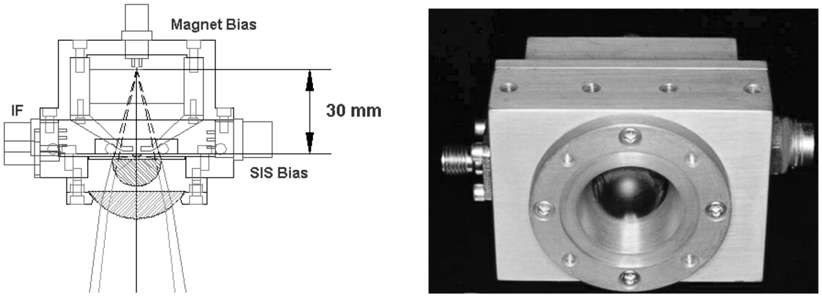

Fig. 4. Optical Configuration of the twin-slot mixer as described by Zmuidzinas *et. al.*

near the 77 K dewar window (Fig. 3). Though this is possible by means of a thick lens, it would introduce unnecessary absorption and reflection loss over the required frequency bandwidth of operation. To complicate matters, the LO injection scheme would have to be changed due to physical constraints imposed upon by the existing cooled waveguide and telescope optics. Both are critical for proper illumination of the telescope, but are in practice difficult to achieve with a cooled plastic lens. In 1993 Filipovic *et. al.* published a comprehensive paper[15] on the far-field patterns and Gausian coupling efficiencies for twin-slot antenna placed on hemispherical lenses with different radii (R) and extension length (L). In the twin-slot mixer[11]-[13] the L/R ratio was 0.291, which is the hyperhemispherical position. This L/R ratio produces a fast F/2.5 beam at the e^{-2} power contour, and hence the need for a plano-convex lens to transform the beam to give a smaller divergence angle. Given the cooled optics[16] and CSO telescope constraints, the optimal beam divergence of the NbTiN mixer turns out to be F/4.2. This equates to a L/R ratio of 0.335 and it is this value that has been chosen for the final twin-slot NbTiN mixer optics configuration.

In order to satisfy the need for a reduced virtual focal distance, we chose the hemispherical radius to be 3.2 mm (0.125 inches). This value of R was deemed to be the smallest practical size possible, especially when the criticality of the SIS

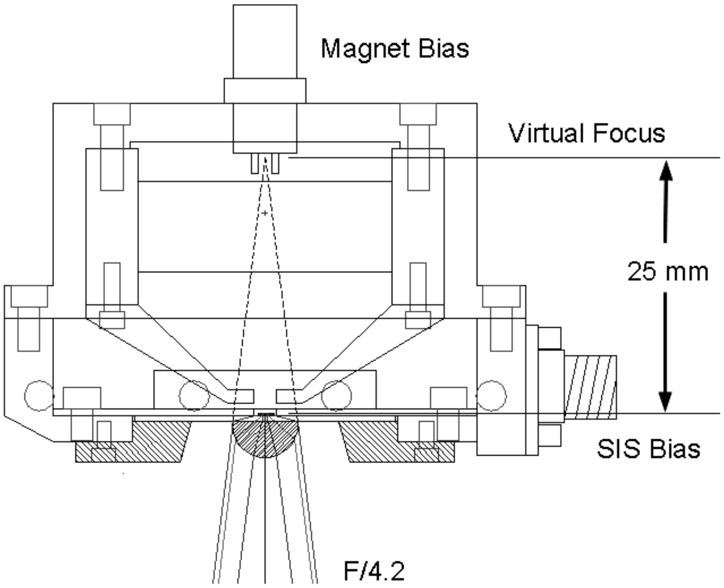

Fig. 5. Modified mixer block with a L/R ratio of 0.335 and 6.35 mm diameter lens.

chip alignment to the extended hemispherical lens is considered. The maximum theoretical gaussian coupling efficiency in the case of L/R = 0.335 turns out to be slightly worse (5%) than with the original L/R= 0.291. This tradeoff was considered acceptable in light of the fact that the successful cooled optics scheme of the 850 GHz waveguide mixer could now be re-implemented for the twin-slot NbTiN mixer.

IV. Receiver Performance

Fig. 7 shows the heterodyne response at 800 and 900 GHz as measured at the Caltech Submillimeter Observatory (CSO). To fully cover the 780-920 GHz atmospheric window two multipliers/LO chains are in use, both from RPG Physics[17]. The 780 - 845 GHz band is covered with a traditional X2 - X3 multiplier, while the 845 to 920 GHz band uses an X2 - X2 - X3 multiplication scheme. The first stage is a high ef-

Fig. 6. Photograph of final optical configuration.

ficiency tunerless doubler, while the remaining doubler and tripler stages employ two tuners each.

The Y-factor response of the twin-slot NbTiN receiver has been included for reference sake. Notice how with increasing frequency the width of the photon step decreases. This is indeed expected for frequencies above 800 GHz (Δgap = 800 GHz) because the photon step from the negative bias side partially cancels the photon step from the positive bias side. The optimal bias condition across the entire frequency band appears to be at 2.10 mV with a LO pump current of $\sim$ $I_c/3$ (40 μA). I_c is defined as the critical current of the junction. The measured leakage current in the junction [22] at 2 mV is 7.4 μA, which corresponds to an R_{subgap} to R_n ratio of 15.

The frequency response of the newly installed NbTiN twin-slot open structure receiver is shown in Fig. 8. The improve-

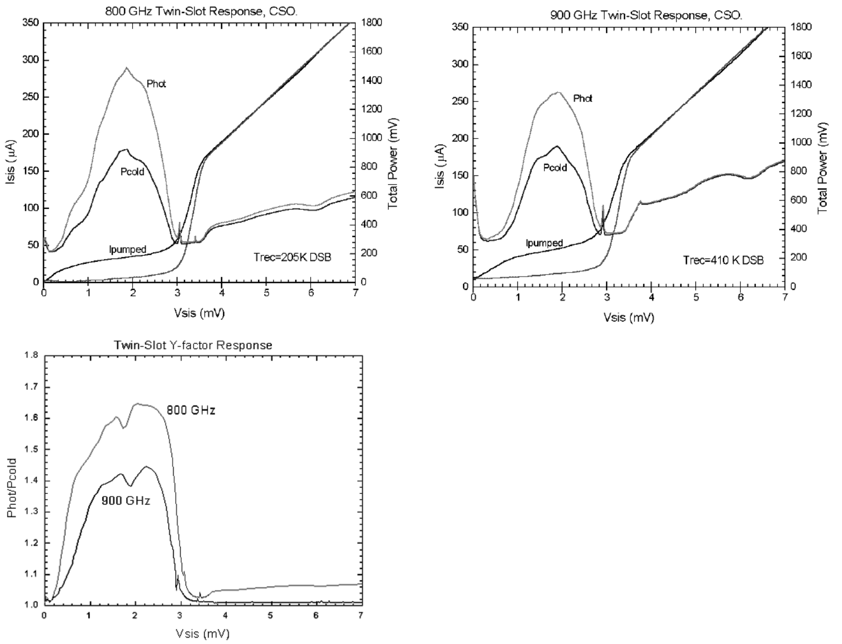

Fig. 7. Receiver and Y-factor response at 800 and 900 GHz.

ment over the in 1997 installed all-niobium waveguide receiver is primarily due to a decrease in the NbTiN wire layer and ground plane transmission line loss (∼5 dB). Note that the front-end optics and IF configurations are identical between the two systems. In the text all noise temperatures have been calculated using the Callan-Welton formula[18][19]. The receiver and mixer properties are summarized in Table II. The optics loss is derived from the intersecting line technique, described by Blundell[20], Ke, and Feldman[21] *et. al.*

t_{RF} * G_{Mix}^{DSB} is the total mixer conversion gain which includes the loss in the optics in front of the mixer. This quantity should be compared against the 850 GHz waveguide results[1], which equated to -12.3 dB at 822 GHz.

T_{Mix} in Table II is the single sideband mixer noise temperature (referred to the input): (T_{Rec} - T_{Optics} - T_{IF}) * (t_{RF}

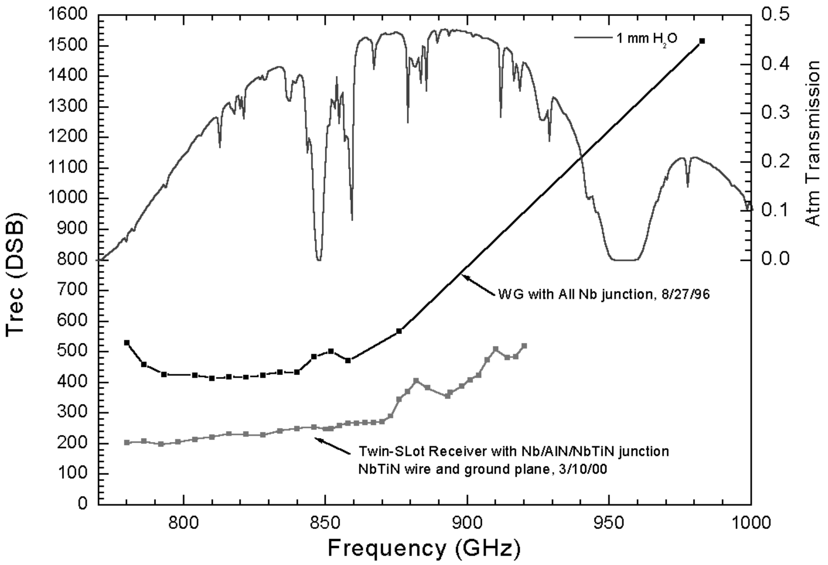

Fig. 8. Receiver sensitivity of the all niobium waveguide, and recently upgraded twin-slot NbTiN open structure mixers.

* G_{Mix}^{DSB}). T_{IF} is the total IF noise contribution, while T_{LNA} is the actual measured noise temperature of the balanced low noise amplifier directly following the mixer. Z_{pumped} is obtained from the LO pumped IV curve in Fig. 7, and is needed to take reflection loss in the shot noise calculations into account. The IF matching network presents a 90 Ω impedance to output of the mixer.

V. Astronomical Observations

Among the first observations carried out with the new receiver we performed 10" resolution maps of two contiguous HDO transitions: $J_{Ka,Kb} = 2_{1,2} \rightarrow\ 1_{1,1}$ at 848.9619 GHz and $J_{Ka,Kb} = 1_{1,1} \rightarrow\ 0_{0,0}$ at 893.6387 GHz (shown in Fig. 9), and HCN J = 10 → 9 at 885.9708 GHz (not shown here) towards Orion IRc2. The weather conditions during the observing runs (January and March 2000) were excellent and provided average zenith transmissions above Mauna Kea as

TABLE II
Measured and Calculated Receiver Parameters at
$V_{sis} = 2.10mV$

Parameters	**800 GHz Data**	**900 GHz Data**
T_{Rec} (K) DSB	205	410
T_{Optics} (K)	70	100
T_{IF} (K)	22	41
$t_{RF} * G_{Mix}^{DSB}$ (dB)	-7.2	-9.9
T_{Mix} (K) SSB	43	55
$h\nu/k$ (K)	38	43
T_{LNA} (K)	4.2 ± 0.3 (measured)	4.2 ± 0.3 (measured)
$\Gamma_{beamsplitter}$ (%)	14	18
Z_{pumped} (Ω)	129	80.5
R_n (Ω)	17.8	17.8
Z_{IF} (Ω)	90	90

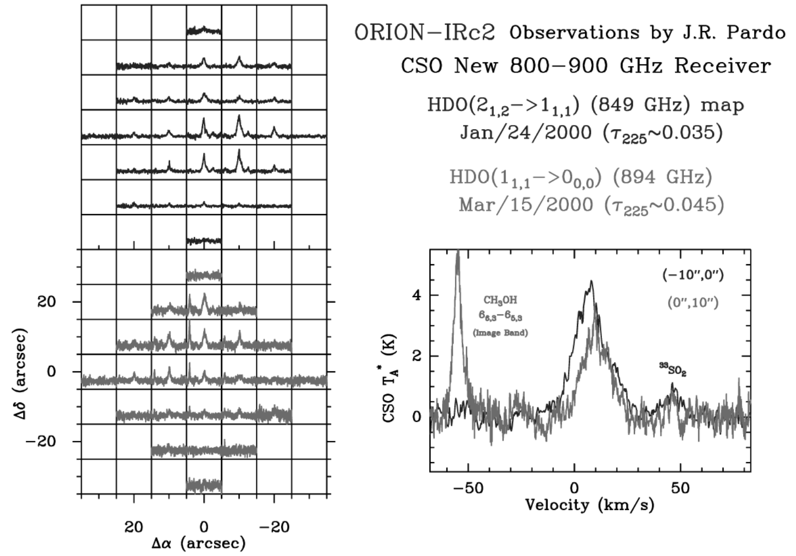

Fig. 9. First Detection of $HDO(2_{1,2} \rightarrow 1_{1,1})$ and $HDO(1_{1,1} \rightarrow 0_{0,0})$ in Orion-IRc2.

high as $\sim$ 38.5% (849 GHz) and $\sim$ 42% (886 GHz). This resulted in system temperatures at 849 GHz as low as 1700 K at the elevation of the source (70 deg) at the beginning of the observations on Jan/24/2000. Integration time for each point was 3 minutes. The observations show a quite compact source for both HDO lines ($\sim$45"). The data are currently being modelled using the same LVG model previously used by Cernicharo [23] *et. al.* (1999) for their analysis of the emission of H_2O at 183.31 and 325.15 GHz (this last line observed also at the CSO) towards the same source. These two H_2O lines have a maser nature in Orion IRc2, so the newly observed (thermal) HDO lines will probably put better constraints on the density, temperature and H_2O abundance estimates of the the emitting regions. The results of this analysis will be published later.

VI. CONCLUSION

A 850 GHz niobium titanium nitride (NbTiN) based twin-slot SIS mixer has been developed and installed at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. The open structure mixer replaces an all niobium based waveguide mixer that was installed as part of a larger receiver system at the observatory in 1997. The $\sim$ 5 dB conversion gain improvement of the new NbTiN mixer is attributed to the use of a higher energy gap superconducting material. The local oscillator (LO) injecting is done at the 4K stage using a set of elliptical mirrors and a beam splitter cooled to 4K. The optics of the twin- slot mixer have been modified to reduce RF front-end loss and to physicaly fit the cooled optics inside the existing cryostat. The upgraded receiver has an uncorrected receiver noise temperature of 205K DSB at 800 GHz and 410K DSB at 900 GHz.

VII. ACKNOWLEGMENTS

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