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InSb heterodyne receivers for submillimeter astronomy

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Abstract

InSb hot electron bolometer mixer receivers have been used for submillimeter line studies of the interstellar medium up to frequencies of about 500 GHz (600μ). Detections of new interstellar lines have been made, such as the ground state fine structure transition of atomic carbon at 492 GHz, and various transitions of molecules such as carbon monoxide and water. The bulk of this work has been performed with the NASA Kuiper Airborne Observatory telescope which is transported to an altitude of about 12,000 km by a C141 aircraft, so avoiding most of the effects of the Earth's atmosphere. Some observations have also been made at ground observatories with the 5 m Hale telescope at Mount Palomar and the NASA Infrared Telescope Facility at Mauna Kea, Hawaii. The heterodyne bolometer receivers have achieved noise temperatures of less than 400 K at all frequencies up to 500 GHz. Development work continues to extend the frequency range further into the submillimeter band.

Introduction

Submillimeter astronomy is a new field of endeavor, which is just emerging and will have a major impact on astronomy in the 1980's. The National Aeronautics and Space Administration currently provides two telescope systems from which such astronomy can be performed, namely the Kuiper Airborne Observatory and the Infrared Telescope Facility at Mauna Kea, Hawaii. It is possible that, in the 1990's, a large space telescope for submillimeter astronomy will be made available. Naturally, to make use of the existing facilities and to prepare for the space facility requires a strong program of detector development for both line (heterodyne receivers) and continuum systems. This paper will outline the current status of line astronomy in the submillimeter and describe the use of InSb heterodyne bolometer detectors, which have already proven successful in certain initial studies in the field.

Many lines of atoms and molecules, which are abundant in the cosmic mix of the interstellar medium, lie in the submillimeter part of the electromagnetic spectrum. Much work has been done at radio wavelengths using the rotational lines of interstellar molecules. However, the fundamental transitions of many molecules, particularly those containing hydrogen (therefore having high rotational frequencies due to their light weight) lie in the submillimeter and cannot be observed in the radio. Also atomic transitions such as the recently detected [1] line of neutral carbon (CI) - see Figure 1 - lie in this range and these will provide new probes into the nature of the interstellar medium. In particular they will provide new information on the chemistry of the interstellar medium, for instance, metal abundances can be traced throughout the galaxy and across external galaxies by means of the simple diatomic hydride molecules. The role of carbon in interstellar chemistry can be traced by comparing the relative abundances of CI, CII, and CO.

The ability to study the high transitions of heavier abundant molecules such as CO will be most valuable. These lines, together with the atomic carbon lines, provide the cooling for clouds of the interstellar medium, so determining the tendency towards collapse and subsequent star formation. Further, the presence in the spectrum of many lines of the same molecule permits a detailed approach towards understanding of radiation transfer within molecular clouds, and tests models of structure and dynamics of the clouds.

Many of these studies can be carried out using the NASA C141 Kuiper Airborne Observatory telescope, even though at 91.5 cm aperture the beamwidth is large, typically 2 min arc. However, for certain atmospheric windows the somewhat larger (3 m) NASA Infrared Telescope Facility at Hawaii can be used. In that case the high resolution available ($\sim$40 arc sec) will allow studies of molecules and atoms in their ground states from neighboring galaxies. The good submillimeter resolution will also be most valuable in permitting observations of molecular envelopes around mass loss stars in a far more comprehensive and detailed manner than has been possible to date.

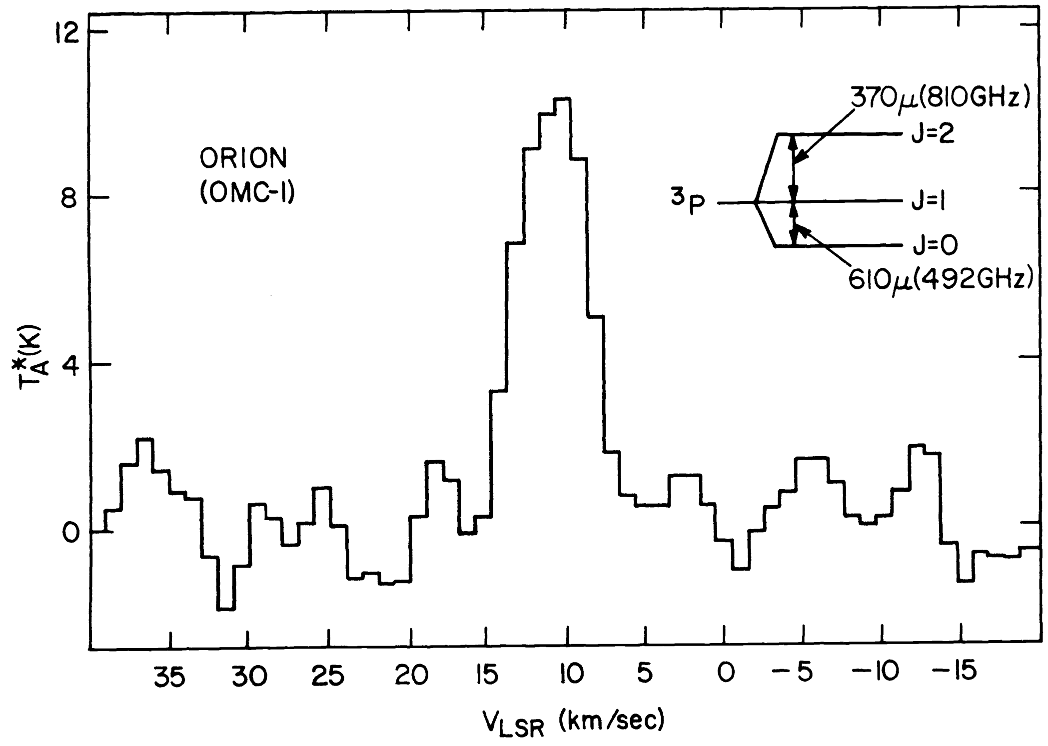

Figure 1. A spectrum of the ground state fine structure line emission of atomic carbon, taken in the direction of the Orion Nebula. The line frequency is approximately 492 GHz and the receiver was an InSb mixer.

An indication of current progress in submillimeter line astronomy is given by the following table of detected strong interstellar lines:

TABLE I

Line	Frequency (GHz) or Wavelength (μ)	Telescope	Receiver System
CO_{3-2}	345	200" Palomar	InSb mixer
$H_2O\ 4_{14} - 3_{21}$	380	C141, NASA	"
CO_{4-3}	460	"	"
CI $^3P_1 - ^3P_o$	492 (610 μ)	"	"
CO_{6-5}	690 (435 μ)	IRTF Hawaii	Schottky Diode
CII $^2P_{3/2} - ^2P_{1/2}$	(157 μ)	C141, NASA	Cooled Grating
$CO_{21-20,22-21}$	(124,118 μ)	"	Cooled Fabry-Perot

It is too early to be clear as to the astronomical impact of the initial work, but both CO and H_2O lines indicate that many regions have strongly excited gas emitting in the submillimeter. The CI detection is particularly encouraging, since this line is a prime coolant and tracer for interstellar gas and is now observed to be at least as ubiquitous as CO. It is exciting to note that infrared techniques are now capable of coarse resolution work at the short wavelength end of the submillimeter, and both Cornell (CII detection) and Berkeley (high CO lines) are active in this area. From the point of view of this paper we note that the initial line detections in the 300-500 GHz range have been with InSb heterodyne bolometer systems.

Receivers

A critical component in submillimeter line astronomy is the receiver. In fact it is clear that at the present time the development of the field is determined by receiver development. There are several viable techniques already operative to some degree, ranging from direct detectors using grating or Fabry-Perot etalons to heterodyne detectors. It seems probable on both theoretical grounds, and from recent experience, that the long wavelength part of the spectrum (say 1 mm - 200 μ) will be dominated by heterodyne systems, whereas the short wavelength end will use direct detection techniques. This paper is concerned with the 1 mm - 200 μ band and will therefore concentrate on heterodyne techniques, and particularly on the InSb heterodyne bolometer which has proved the most productive system to date.

So far only two classes of heterodyne receivers have been successfully used for submillimeter astronomy: the diode mixer and the bolometer mixer. In the future it may prove possible to use photon assisted tunneling devices such as Josephson or quasiparticle junctions. Also semiconductor photodetectors should prove useful at short wavelengths.

Figure 2 shows performance figures for a variety of mixer detectors. The room

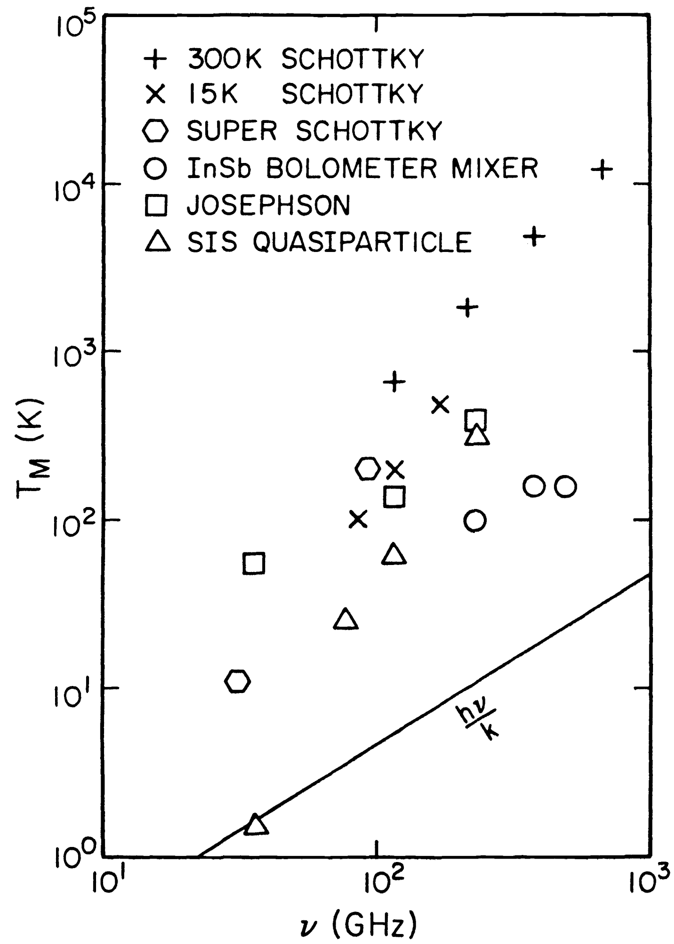

Figure 2. Mixer noise temperatures for a variety of heterodyne receivers.

temperature Schottky diode mixer results are from Carlsen et al [2] (1979), Erickson [3] (1978), and Fetterman et al [4] (1978). Cooled Schottky diode results are from Linke [5] (1979). Superconducting junction results are from Dolan et al [6] (1979), Richards et al [7] (1979) for quasiparticle junction; McCall et al [8] (1977) for super Schottky mixers; Taur and Kerr [9] (1978) and Edrich [10] (1978) for Josephson devices. InSb mixer results are from our own studies.

The InSb Bolometer Mixer

This device is a relatively simple liquid helium cooled bulk single crystal element, which, when mounted in a waveguide, acts as a mixer for wavelengths down to $\sim \frac{1}{2}$ mm (600 GHz). It has an already demonstrated performance to 500 GHz and has been used for mm and sub-millimeter astronomy since 1973.[11] Given adequate local oscillator power ($\sim 10^{-6}$ watts) the receiver noise temperatures range from 150 K at 115 GHz to about 350 K at 500 GHz.

At liquid-helium temperatures in very pure InSb ($N_D - N_A \sim 3 \times 10$ cm^{-3}) there are still some conduction electrons which are not frozen out. The electrons interact only weakly with the lattice so that a small current in the bulk material will raise the electron gas temperature (T_e) considerably. In this system the mobility is controlled by ionized impurity scattering and is a strong function of electron gas temperature. This is the basis of the hot-electron bolometer effect [12].

When the bolometer is mounted in a waveguide, so that its dimensions are small compared with a wavelength, it acts as a mixer in that it responds to the square of the electric field at that point in the guide. Current flow causes an increase in electron gas temperature and a change in mobility and resistance of the device. A qualitative view of the operation of the mixer may be obtained by considering the flow of power from the microwave fields to the conduction electron system and to the lattice. Under constant current bias conditions the incident power (P_{in}) is described by

$$P_{in} \approx P_{dc} + P_{LO} + 2(P_{LO}P_S)^{\frac{1}{2}} \exp(i\omega t) \qquad (1)$$

where $P_{dc} = I_c{}^2R_o$, P_{LO}, and P_S are the dc, local-oscillator, and signal powers, respectively; ω is the angular intermediate frequency (difference between local oscillator and signal frequencies); P_{in} is balanced by the power (P_{out}) required to raise the conduction electron temperature by an amount ΔT, i.e.;

$$P_{out} \approx K\Delta T + \frac{Cd(\Delta T)}{dt} \qquad (2)$$

where K is the thermal conductance to the lattice and C the conduction electron thermal capacity. Using the fact that the mobility is proportional to $T_e{}^{3/2}$ it is found from (1) and (2) that the voltage across the bolometer is given by

$$V_b \approx I_oR_o \left[1 - \frac{3/2(P_{dc}) + P_{LO}}{K'T_o} - \frac{3(P_{LO}P_S)^{\frac{1}{2}}}{K'T_o} \frac{\exp(i\omega t)}{1 + i\omega\tau'}\right] \qquad (3)$$

where $K' = K + (3/2)\ (P_{dc} + P_{LO})/T_o$, $\tau' = C/K'$, and T_o is the lattice temperature.

The terms in the bracket of (3) are the Ohm's law voltage, deviation from Ohm's law (hot-electron effect), and signal voltage, respectively. A more complete description of this approximate mixer formalism is given in reference [11].

A disadvantage exists; namely, the instantaneous bandwidth is only $\sim$ 1 MHz. This is due to the fundamental energy relaxation time τ' (equivalent to recombination time in a photoconductor). However, since the signal-to-noise one may achieve for heterodyne mixers is $\propto \sqrt{\Delta\nu}/T_N$ the 200 K InSb mixer ($\sim$1 MHz bandwidth) is as good as a 2000 K diode mixer ($\sim$100 MHz bandwidth). So at frequencies above 300 GHz the InSb mixer is still the most effective receiver at the present time; spectra are taken by sweeping the local oscillator. Of course, if the experiment requires less bandwidth than 100 MHz the InSb receiver becomes correspondingly more effective. In particular, if a map at line center is of astrophysical interest (which is the case for many sources), the low noise temperature provides a most impressive capability relative to other receiver systems.

Figure 3 shows the system layout for use on telescopes such as that of the NASA Kuiper Airborne Observatory.

A typical mounting arrangement for this receiver system is seen in Figure 4 which shows the 492 GHz (carbon line) receiver fixed to the detector port of the aircraft telescope.

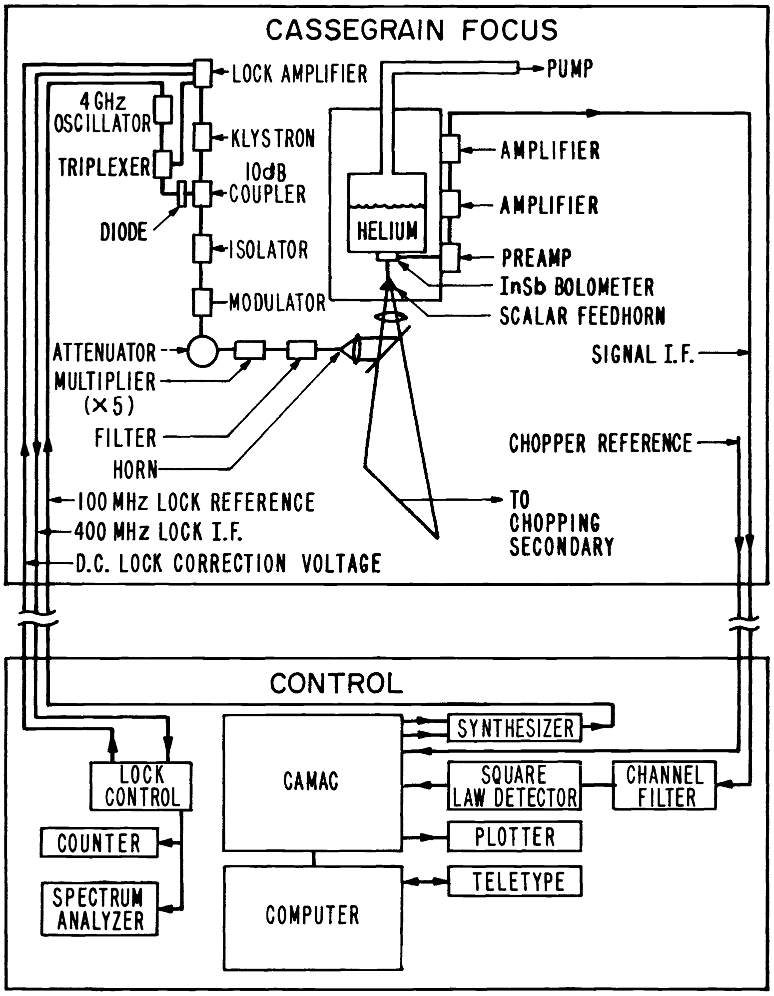

Figure 3. A block diagram of the heterodyne bolometer receiver system

At the moment the InSb receiver provides the simplest and most effective system for submillimeter astronomy. To some degree this is due to the low power requirement for the local oscillator ($<10^{-6}$ watts), which can be generated by millimeter wave klystrons driving Schottky diode harmonic generators. When the InSb receiver was initially developed it was projected that there would be no problem in extending the frequency range to 500 GHz [11]. This has been achieved; the question now arises as to how much further in frequency the system could be extended and whether the noise temperature could be yet further decreased or the bandwidth increased. These questions can only be answered by development work.

One limiting factor is the difficulty of obtaining even 10^{-6} watts of local oscillator power at frequencies >500 GHz. This can be remedied by the use of high power fundamental oscillators, such as carcinotrons, or by development of more efficient high frequency multipliers. A second, more fundamental problem is that from measurements of the material response to radiation as a function of frequency, or from the theory of free electron absorption of radiation in semiconductors, it is known that the responsivity to radiation will start to drop above 600 GHz (shortward of 500 μ). At frequencies above the plasma frequency the conductivity is given by [12]:

$$\sigma(\omega) = \frac{\sigma_o}{1 + \omega^2 \tau^2} \qquad (4)$$

where τ is the momentum scattering time. This leads to an absorption coefficient;

$$\alpha = \frac{\sigma_o}{c\varepsilon_o} \left(\frac{1}{\varepsilon}\right)^{\frac{1}{2}} \frac{1}{1+\omega^2\tau^2} \qquad (5)$$

For material optimized for lower frequencies ($N_D - N_A \sim 5 \times 10^{13}$ cm^{-3}; $N_D \sim 7 \times 10^{14}$ cm^{-3}) $\tau \approx 3 \times 10^{-13}$ secs, so that the ω roll off is $\sim 3 \times 10^{12}$ or we have an expected frequency limit of $\sim$ 500 GHz. To improve on this directly one could decrease τ or, to achieve a given α, increase σ_o. τ is determined by the number of ionized impurity centers and the degree of compensation. To accommodate higher frequencies implies increasing the impurity content while maintaining the relative compensation. σ_o will largely be determined by $N_D - N_A$, so that increasing the number of impurities seems to be beneficial on all counts. An independent approach is to take advantage of the phenomenon of cyclotron resonance to achieve high absorption coefficients at related frequencies. The photoresponse of InSb peaks at a

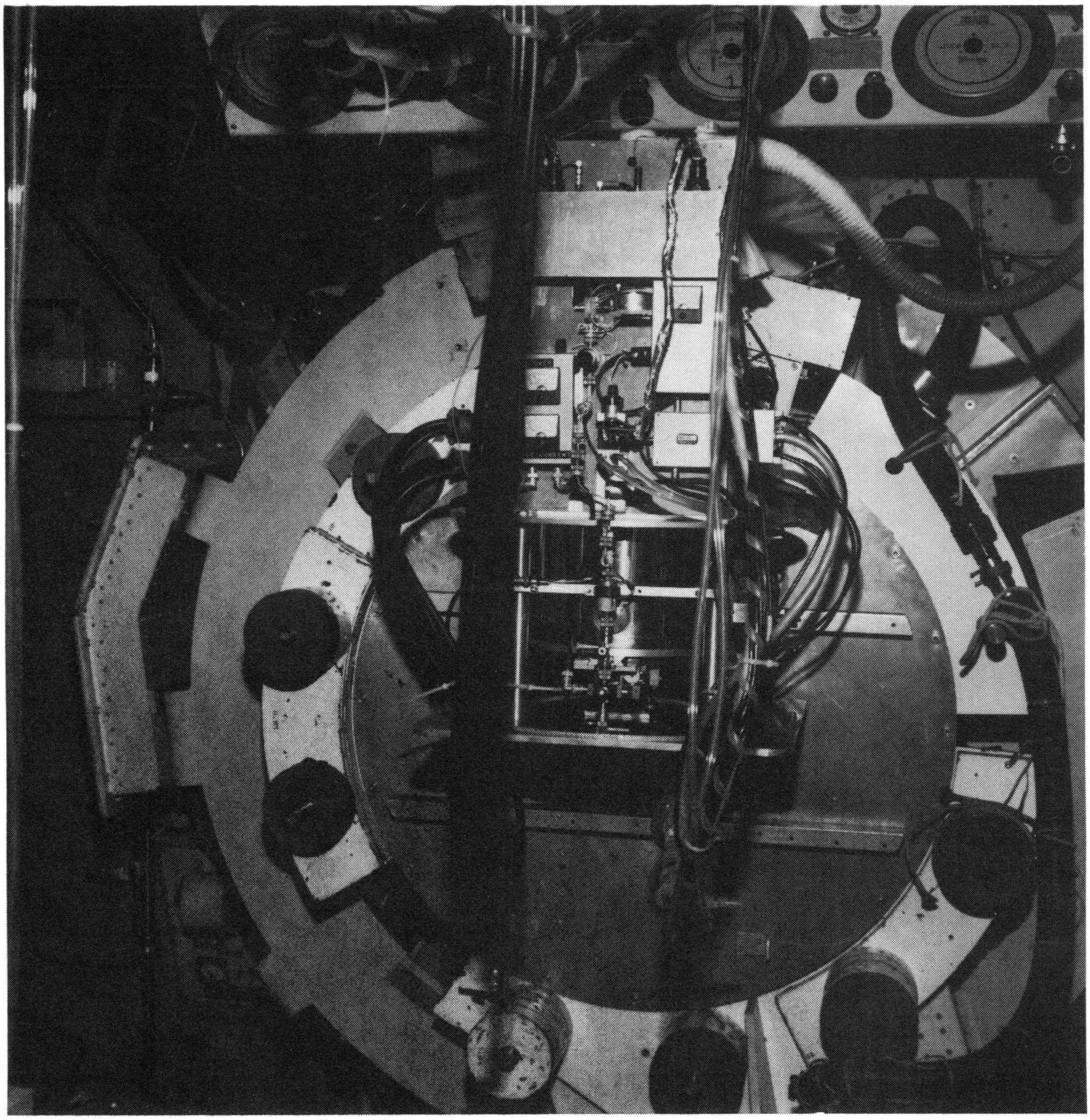

Figure 4. Mounting arrangement for the 492 GHz receiver on the Kuiper Airborne Observatory telescope.

frequency:

$$\nu \approx \frac{\omega_c}{2\pi} = \frac{eB}{2\pi m^*} \tag{6}$$

where B is the magnetic field and m^* is the electronic mass. This effect was initially used by Putley to increase the response at low field values, since the resistance is increased. That would be of no value in this case, because the multitransistor amplifiers in use in our present systems make no serious contributions to the system noise. However, the effect will be of considerable value in increasing the absorption coefficient at $\nu \approx \omega_c/2\pi$. A field of about 6 KO_e will allow resonance at 500 GHz, so that the submillimeter range is covered by easily available magnets which can fit within a receiver dewar.

Conclusions

The above arguments present a brief outline of the available development concepts which would be expected to lead to a factor of two extension in frequency coverage for the InSb system. Given the current system capability of $T_r \sim 350$ K at 500 GHz it seems reasonable that noise temperatures of 700 K or less could be achieved at 1,000 GHz, on the basis that the photon noise is likely to scale with $h\nu$ and that the material electronic absorption coefficient can be increased by one of the above mentioned procedures.

Acknowledgements

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References

1. Phillips, T. G., Huggins, P. J., Kuiper, T. B. H. and Miller, R. E., "Detection of the 610 Micron (492 GHz) Line of Interstellar Atomic Carbon", Astrophys. J., 238, L103. 1980.
2. Carlson, E. R., Schneider, M. V. and Mc Master, T. F., "Subharmonically Pumped Millimeter-Wave Mixers", IEEE Trans. MTT-26, 706. 1978.
3. Erickson, N. R., "A 0.9 mm Heterodyne Receiver for Astronomical Observations", IEEE Int. Mic. Symp. MTT-S, 438. 1978.
4. Fetterman, M. R., Tannenwald, P. E., Clifton, B. J., Parker, C. D., Fitzgerald, W. D. and Erickson, N. R., "Far IR Heterodyne Radiometric Measurements with Quasi-Optical Schottky Diode Mixers", Appl. Phy. Lett., 33, 151. 1978.
5. Linke, R. A. Personal communication.
6. Dolan, G. J., Phillips, T. G. and Woody, D. P., "Low Noise 115 GHz Mixing in Superconducting Oxide-Barrier Tunnel Junctions", Appl. Phys. Lett., 34, 347. 1979.
7. Richards, P. L., Shen, T. M., Harris, R. E. and Lloyd, F. L., "Quasiparticle Heterodyne Mixing in SIS Tunnel Junctions", Appl. Phys. Lett., 34, 345. 1979.
8. McCall, M., Bottjer, M. F., Chase, A. B., Pederson, R. J., Silver, A. H., and Tucker, J. R., "The Super-Schottky Diode at 30 GHz," IEEE Trans. MAG-15, 468. 1979.
9. Taur, Y. and Kerr, A. R., "Low Noise Josephson Mixers at 115 GHz Using Recyclable Point Contact", Appl. Phys. Lett., 32, 775. 1978.
10. Edrich, J., Private communication.
11. Phillips, T. G. and Jefferts, K. B., "A Low Temperature Bolometer Heterodyne Receiver for Millimeter Wave Astronomy", Rev. Sci. Instrum. 44, 1009. 1973.
12. Kinch, M. A. and Rollin, B. V. "Detection of Millimeter and Submillimeter Wave Radiation by Free Carrier Absorption in a Semiconductor", Brit. J. Appl. Phys., 14, 672. 1963.