A Practical Schottky Mixer for 5 THz (Part II)

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Abstract

A mixer using a GaAs Schottky diode in a corner reflector mount has been built and used for astronomical observations near 5 THz. A receiver noise temperature of 70,000 (DSB) was measured at 4.75 THz with an ambient temperature mixer aboard NASA's Kuiper Airborne Observatory. Although this sensitivity is somewhat worse than a value extrapolated from lower frequency work, it is adequate for observations of the 63 μm O I fine structure line in atmospheric and the stronger astronomical sources. The noise performance of the 5 THz receiver is compared to that of other Schottky systems operating in the 1-5 THz frequency range.

1. Introduction

At last year's meeting a design was presented on a Schottky diode mixer for astronomical observations at 5 THz [1]. The scientific application required a mixer of modest sensitivity that could be produced on the short time scale of a few months. Hence the plan was to use a modified form of a pre-existing corner reflector mixer, rather than to undertake a fully optimized design. Calculations showed that a mixer with an antenna length near 30λ could achieve an acceptable main beam efficiency of 43% and be fabricated with a mount previously used for a 4λ mixer at 810 GHz (370 μm).

The scientific objective was the observation of the 4.75 THz (63 μm) fine structure line of neutral atomic oxygen (O I) in interstellar gas. O I line emission is strongest from the peripheries of interstellar clouds where molecules such as CO, OH, and H_2O are photodissociated by interstellar UV radiation. Because this wavelength region is completely absorbed by water vapor in the earth's troposphere, observations must necessarily be made from altitudes higher than the tropopause near 12 km. The only facility capable of doing this was NASA's Kuiper Airborne Observatory (KAO). Unfortunately, this aircraft and its 91 cm telescope were scheduled to be permanently grounded after September, 1995, in order to promote the development of a new airborne observatory: the Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA, a 747 aircraft with a 2.5 m telescope, has just been approved and will not be available until the year 2000 at the earliest, which means a 4-5 year hiatus for airborne astronomy [2]. Hence, our effort to produce a multi-THz mixer had to be speeded up drastically if we were to meet the 1995 cutoff and do the much desired 63 μm O I observations.

2. Design & Performance of the 5 THz Mixer

Whereas most of the Schottky mixers we have used for astronomy in the 1-2 THz band were cooled to 77 K to improve T_{sys}, the 5 THz mixer is intended to be operated "warm" - at ambient temperature. Three factors favor this decision: (1) Absorption losses from dielectric materials are higher at 5 THz, and absorption losses from a cryostat window would offset any possible gains in mixer sensitivity by cooling. (2) Cooling actually doesn't help that much intrinsically. Lab measurements indicate that cooling a type 1T15 mixer increases the series resistance R_s which reduces the IF coupling efficiency as well as the thermal noise component, and hence no net benefit accrues. (3) Cooling to 77 K places additional mechanical stresses on the contact to the sub-micron diameter anode which increases the likelihood of failure on repeated thermal cycling. We have had a very limited number of good contacts with 1T15 diodes, and were loath to risk the few good ones we had. If we failed in 1995, there would be no second chance this century.

The mechanical design of the mixer is a longwire antenna and corner (or roof) reflector [3]. The optimum design for the spacing s of the apex of the roof-reflector from the antenna wire is 3.2λ for a mixer with a 30λ antenna length. At $\lambda = 63\,\mu$m, this means a spacing s of 202 μm. Several mixers with these dimensions were constructed and tested, but none performed as well at 63 μm as the unit constructed with a 25.2λ antenna for the measurements done at 86 μm [1]. Unfortunately, mechanical constraints limited the dimension s to be >250 μm for this mixer, which is about 17% bigger than optimum for 63 μm work. Fortunately the main beam efficiency of the mixer is not strongly affected by variations in the length s within a 20% tolerance.

A schematic diagram of the airborne receiver is given in Figure 1; additional details may be found in reference [4]. The local oscillator is an optically pumped far-infrared gas laser, operating on the 4751.3409 GHz transition of $^{13}CH_3OH$ [5] which is 6.564 GHz away from the rest frequency of the O I line at 4744.777 GHz [6]. The mixer is a type 1T15 diode from UVa Semiconductor Device Laboratory, and is optimally biased at a constant current of 300 μA with an LO-induced voltage change of 120 mV. The mixer operates at an ambient temperature of 293 K, but the 6.6 GHz IF amplifier is cooled to 77 K, where it achieves a noise temperature of 30 K. T_{sys} at 4.75 THz is measured in flight to be 70,000 K (DSB). This is almost a factor of 3 worse than a projection drawn earlier (and naively) from extrapolations of lower frequency results [1]. Although 1 m of the signal path within the spectrometer is not enclosed, absorption from the intervening air is estimated to be only

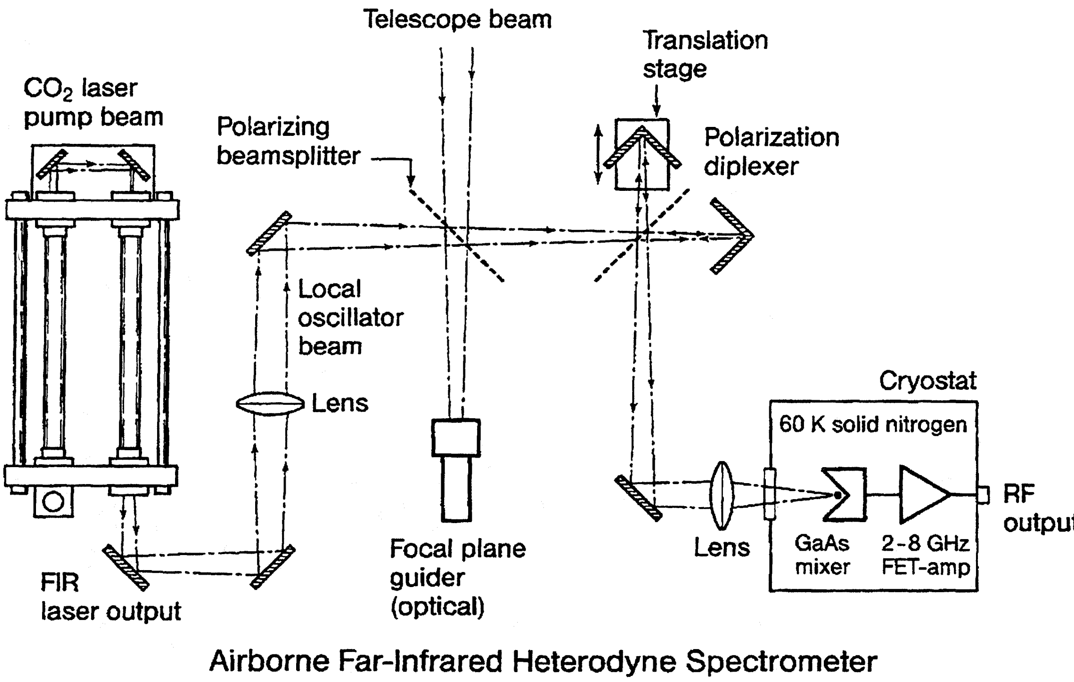

Figure 1: Schematic of heterodyne spectrometer. The cryostat temperature is 77 K.

7%, when averaged at the O I and image frequencies. Cabin air in the aircraft air is very dry with only a 3% relative humidity, because the KAO flies at an altitude of 12.5 km, which is usually above the tropopause and most of the atmospheric water. The IF signal is analyzed by a 400 channel acousto-optic spectrometer (AOS) with a channel resolution of 3.2 MHz (0.2 km s^{-1}) and a bandwidth of 80 km s^{-1} at the O I line frequency.

A good measure of proper coupling between mixer and telescope is given by observations of the Moon. If the Moon appears "warmer" than the absorbing blade of a room temperature "load chopper", then coupling of the main beam of the mixer to the telescope is within tolerance. We estimate an aperture coupling efficiency of 0.5, which is about 70% of the theoretical optimum that can be achieved with the 0.2 blockage ratio of the KAO telescope.

3. Observations of the 63 μm O I Line in the Orion Nebula

Observations of the O I line were done from the KAO on the nights of 1995 September 9 and September 11. Figure 2 shows the line profile measured near the source θ^1C in the Orion Nebula. The net Doppler shift of the Orion source was 2 km s^{-1}, which is not enough to shift the emission line completely away from interfering absorption by atomic oxygen in the earth's thermosphere (85-200 km altitude). The unplotted channel near 8 km s^{-1} V_{LSR}

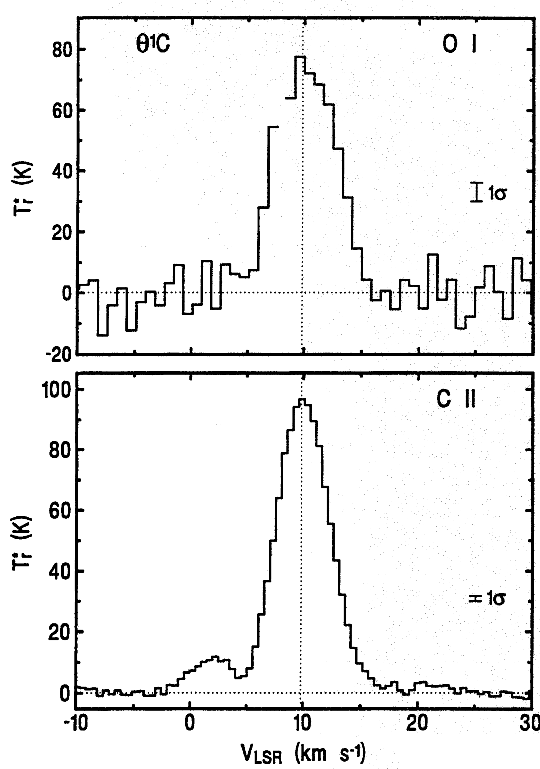

Figure 2: Observed 63 μm line of atomic oxygen from Orion

in Figure 2 is the region of the spectrum where the interfering absorption exceeds 50%. A spectrum of the Moon (with no intrinsic features) shows that the terrestrial O I line is optically thick (100% absorbing) at line center, but fortunately very narrow. Theoretically the Orion observations could have been done at a different time of the year, when the net Doppler shift would preclude interference from terrestrial O I, but such a time was not available during this final year of KAO flight observations.

The integrated intensity that we measure for the O I line is quite similar to the value reported previously from Fabry-Perot observations at much lower spectral resolution. The significance of our O I measurement lies in the linewidth. For the first time we are able to measure the true linewidth to be 6.8 km s^{-1} (FWHM), and also to determine that it is broadened over the intrinsic linewidth of 3.6 km s^{-1} by optical depth effects [7]. The peak line intensity (measured in T_r^* units common in radio astronomy) tells us that the gas kinetic temperature is close to 200 K, which is considerably less than the value of 300 K currently used in theoretical models of photodissociation regions of interstellar clouds. Our accurate measurement for the gas temperature allows us to make better estimates of abundances and excitation conditions of neutral oxygen and other atomic species (such as ionized carbon) in such regions. A comparison spectrum of ionized carbon emission at 1.9 THz (158 μm) is also shown in Figure 2. These data were taken in 1991 November with a cooled mixer with a $T_{sys} = 5000$ K (DSB).

4. Schottky Performance Review

The sensitivity of the 5 THz mixer can be seen in relation to our other Schottky mixers in Figure 3. Here we plot T_{sys} from 1.0 to 4.8 THz for various receivers constructed over the past 8 years. A variety of diode types have been used, but all were fabricated at the Semiconductor Device Laboratory of the University of Virginia. All receivers were used for astronomical observations on the KAO except that indicated by the 84 μm measurement. Measurements specific to T_{mix} have not been made; the data points include the noise contributions from optics losses and various IF amplifiers. All measurements are for cooled (77 K) mixers and amplifiers except those at 84 μm and 63 μm, which have warm mixers but cooled amplifiers. Antenna lengths (when measured in λ) also differed across the band. At 1 THz we use a 4λ antenna; at 1.9 THz and 2.5 THz: 9.7λ, at 3.5 THz: 25.2λ, and at 4.75 THz: 34λ. (Yes, all antenna lengths are nearly the same physically.) From Part I [1], we see that the main beam efficiency of a mixer with an antenna of constant physical length drops from 0.67 to 0.42 over the 1 to 5 THz band. Despite the differing conditions, the measurements probably indicate the relative performance one can expect from Schottky mixers in this frequency range. Improvements of more than a factor of 2 at any frequency will be hard to realize. Most of our effort has been placed at 1.9 THz (the C II line frequency), and this is indicated in the plot by a somewhat lower noise temperature than the linear trend of 3600 K (DSB)/THz shown by the lower straight line. The effective quantum efficiency at 1.9 THz is about 1% (100 hν). Above 2.5 THz the performance of available diodes degrades rapidly, consistent with a total noise proportional to $T_{sys} = f(a + bf^2)$, with a "knee" of increased noise (over a simple linear response) somewhere between 1.6 THz and to 2.5 GHz. The noise of Schottky mixers should be compared to SIS, which will soon achieve 5-10 hν (per unit bandwidth) below 1 THz [8], and photoconductive mixers such as HgCdTe photodiodes, which have achieved 5 hν sensitivity in the mid-infrared near 30 THz ($\lambda = 10\,\mu$m) [9].

5. A Future for Schottky Mixers ?

Astronomy

The effectiveness of Schottky mixers in astronomy is limited by the sensitivity plotted in Figure 3. Below 2 THz spectral lines are strong and noise is relatively low, and so many types of observations are possible. Above 2 THz lines tend to get weaker (in a T_r^* sense), whereas noise gets rapidly worse, and applications are more restricted. Of course, the SOFIA observatory with its larger telescope will enable more types of observations at all frequencies, but the preferred frequency domain for Schottky work will still be <2 THz. This frequency restriction makes the future for Schottky mixers in astronomy look bleak. Competing technologies with potentially superior noise performance, such as SIS up to 1.2 THz and HEB up to 2 THz (or perhaps even higher), will soon relegate Schottky mixers to the museum display case. Astronomy in the next millennium needs quantum-noise-limited performance, and Schottky mixers just can't do it.

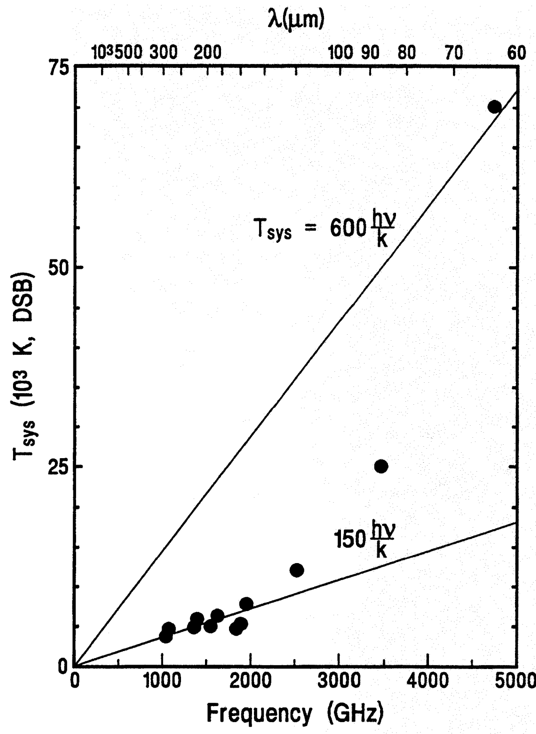

Figure 3: Measured system noise temperature as a function of frequency

Atmospheric Sciences

The bleak forecast given above should be contrasted with excellent prospects for Schottky technology in the atmospheric sciences. In situations where optimum noise performance is not required, but convenience and simplicity are paramount, Schottky mixers will still find applications. Many long duration observations in remote sensing from "remote locations" (e.g., space or Antarctica) need a technology that does not require the complexity of stored cryogens or attended operation. Other cases of high signal measurements also fall naturally into the Schottky's domain. For example, Schottky mixers with their high saturation levels have an advantage for measurements of atmospheric lines in absorption against the solar continuum. Many atmospheric lines in the far-infrared are also optically thick, and measurements of line emission against a cold reference (i.e., load chopping) are also possible. In particular, the fine structure lines of atmospheric atomic oxygen at 63 μm and 145 μm lend themselves to this type of study. Figure 4 shows the 63 μm O I line measured in absorption against the lunar continuum. This is the first fully resolved spectrum of this Doppler broadened line, from which one can measure the line width and estimate the temperature of thermospheric oxygen in the earth's atmosphere. The linewidth of the optically thick feature is 20 MHz (FWHM), equivalent to a Doppler width of 1.3 km s^{-1}. For gas at 300 K the Doppler width of an optically thin line would be 15 MHz. Neutral oxygen is thought to lie exclusively at altitudes higher than 50 km, where the pressure is $<$1 mbar, and so one would not expect to see any pressure broadening effects. Of course for temperature measurements it would perhaps have been better to observe the line in emission relative to a load-chopped reference source, rather than the sky-chopped observation of the Moon. But the intent of the observation was to calibrate the Orion O I spectrum mentioned above. This atmospheric O I line can be observed in absorption against the Sun for a factor of 15 improvement in signal-to-noise. The quality of the spectrum would then be adequate to permit a detailed analysis of the abundance and temperature of neutral oxygen, even though the O I line is optically thick.

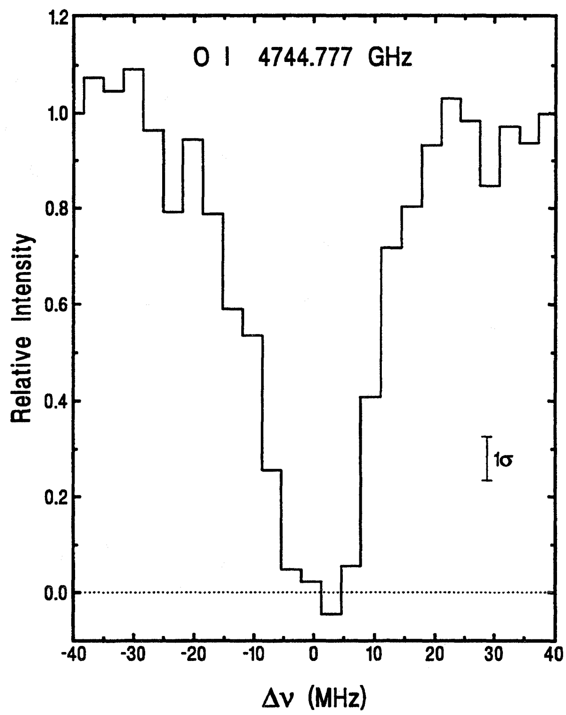

Figure 4: Absorption line from atomic oxygen in the Earth's thermosphere

Another application worth mentioning is measuring water vapor in the Earth's upper atmosphere. This can be done quite effectively with a warm Schottky mixer simultaneously observing the 380 GHz line of H_2O and the nearby 368 GHz line of O_2 line which is saturated. The best implementation for this mixer would be a planar Schottky diode in a waveguide mount. A room temperature receiver of this type would be considerably more sensitive and reliable than the cryogenic Fabry-Perot spectrometer typically used in airborne measurements of water vapor. So, yes there is a future for Schottky mixers - a future in remote sensing of the Earth and its atmosphere.

This work was supported by NASA Grants NAG2-753 and NAGW-2954.

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