A Practical Schottky Mixer for 5 THz

A. L. Betz and R. T. Boreiko
Center for Astrophysics and Space Astronomy
University of Colorado, Boulder

I. Scientific Motivation

The wavelength band between 60 and 120 μm is particularly important for observations of the interstellar medium, for it is here that the cores of galactic molecular clouds radiate most of their energy. Both continuum radiation from warm dust grains and line radiation from ions, atoms, and molecules are important cooling mechanisms for material warmed by the intense UV radiation from newly formed stars. Velocity gradients within the clouds are so small that the resolving power of the spectrometer should exceed 10^6, if the intrinsic line shapes (and the information they contain) are not to be degraded. Heterodyne receivers capable of such resolution have so far only been operated at wavelengths >118 μm (2.5 THz) [1]. Of particular interest to astronomers are observations of the fine structure line from neutral oxygen (O I) at 63 μm (4.75 THz). This transition is the major cooling line for the "warm" (T = 200 K) and "dense" (n $\geq 10^6$cm^{-3}) gas in the cloud core. Of course this radiation cannot penetrate the earth's atmosphere, so all observations must be done above the tropopause with aircraft or space-borne instruments. To date only grating and Fabry-Perot spectrometers have been successfully used for observations of the oxygen line, albeit with far less spectral resolution than that possible with heterodyne techniques.

We can estimate some of the line parameters for the oxygen line by comparison with another fine structure line emitted by these clouds: the 158 μm line of ionized carbon (C II). This longer wavelength line has been observed with a laser heterodyne spectrometer aboard NASA's Kuiper Airborne Observatory (KAO) for over 7 years now [2]. Heterodyne observations at 3 MHz (0.5 km s^{-1}) spectral resolution have shown that the C^+ emission may in some sources be optically thick, in which case its function as a major cooling mechanism is somewhat impaired. For the conditions expected in cloud cores, emission from the 63 μm line should be even more optically thick (saturated), but no direct spectroscopic evidence exists. Up to now most theoretical analyses of excitation temperatures in photodissociated gas have been based simply on the observed intensity ratio of unresolved 158 μm carbon and 63 μm oxygen lines, which are assumed to be optically thin. Therefore the derived excitation temperatures (and element abundances) could be erroneous if either line is optically thick. A better way to determine the gas excitation temperature would be to measure the peak brightness temperatures of resolved O I and C II lines. If a case for optically thick emission can be made, then the peak temperature yields the excitation temperature directly.

Fabrication of a mixer for 63 μm using either waveguide or a standard 4 λ antenna corner-reflector design [3] would be an exercise in tedium and disappointment. Fortunately, a practical solution exists within the corner reflector design model, and that is to use an antenna length much greater than 4 λ.

Our plan is to use an antenna length in the range of 20-30 λ for observations at 63 μm, and thereby to avoid some of the tight technical constraints imposed by a shorter antenna length. Another constraint is the time schedule – the only available observational platform, the KAO aircraft, will likely no longer be in service after September, 1995.

II. Technical Plan

(A) Background on Corner Reflector Mixers

Heterodyne receivers using GaAs Schottky diodes and far-infrared lasers as local oscillators (LOs) have proven themselves to be practical instruments for astronomical spectroscopy at wavelengths between 400 and 118 μm. Although their dominance for ultra-high resolution observations ($\lambda/\delta\lambda > 10^5$) arises primarily from the lack of practical competing technologies, it should be borne in mind that they are still sensitive enough for a number of problems of astronomical interest, in particular the study of the strongest FIR lines which dominate the cooling of molecular clouds. Although SIS mixers undoubtedly will prove superior to Schottky diodes at the longer FIR wavelengths ($> 330\,\mu$m) sometime soon, there is still a future for Schottkys and laser-LOs at the shorter FIR wavelengths.

The advance of Schottky mixers to submillimeter and FIR wavelengths began with the introduction of the open resonator corner-reflector mixer design. Most corner reflector mixers now in use are similar to the original design of Krautle *et al.* [3] in that they have a 4 λ "long-wire" antenna spaced a distance of 1.2 λ from the apex of a 90° roof-type reflector. The tip of the antenna contacts the anode of a small ($<1\,\mu$m) GaAs Schottky diode, which is the active mixer element. There is nothing magic about the 4 λ antenna length, but it does yield a main beam with good symmetry in the E- and H-planes, with an f/3 divergence which is easily matched to the telescope. Further work on this general design showed that although a better main beam efficiency can achieved with a shorter antenna length of 1.35 λ (spaced 0.9 λ) [4], antenna lengths much longer than 4 λ could be effectively used if the reflector spacing is appropriately chosen [5].

The principal advantage of the open-structure corner-reflector design is that it is simple and has relatively few critical dimensions, all of which are larger than λ. Consequently, in comparison with the more traditional waveguide structure with its sub-λ dimensions and three-dimensional constraints, corner-reflector mixers are much easier to fabricate and generally have lower losses. The long-wire character of the antenna, however, does introduce more sidelobe structure to the beam pattern than does a single-mode waveguide mixer, but the penalty of about 3 dB in main-beam efficiency for the "long-wire" seems worth the price when the alternative may be no mixer at all.

As we go to ever shorter wavelengths, the 4 λ antenna itself becomes difficult to fabricate and position accurately. At 158 μm where the important C II fine-structure line occurs, the 4 λ antenna is only 0.63 mm long, and for the equally important 63 μm O I line the length is only 0.25 mm. In an attempt to keep the mixer dimensions much larger than common machining tolerances, we have investigated the efficiency of higher order antennas with lengths of 10 to 30 λ. For the 63 μm O I line, a 25 λ antenna length is physically identical to a 4 λ design for 370 μm, which we know from experience to be mechanically practical.

The efficacy of antenna lengths longer than 4 λ is demonstrated by our observations of the 158 μm C II line, where we used an antenna length of 9.7 λ [2]. As will be shown below, for any antenna length $> \lambda/2$, most of the radiation can be confined to a single main lobe if the distance s between the reflector apex and the antenna wire is correctly adjusted. For the 9.7 λ antenna mentioned above, $s = 1.7\,\lambda$.

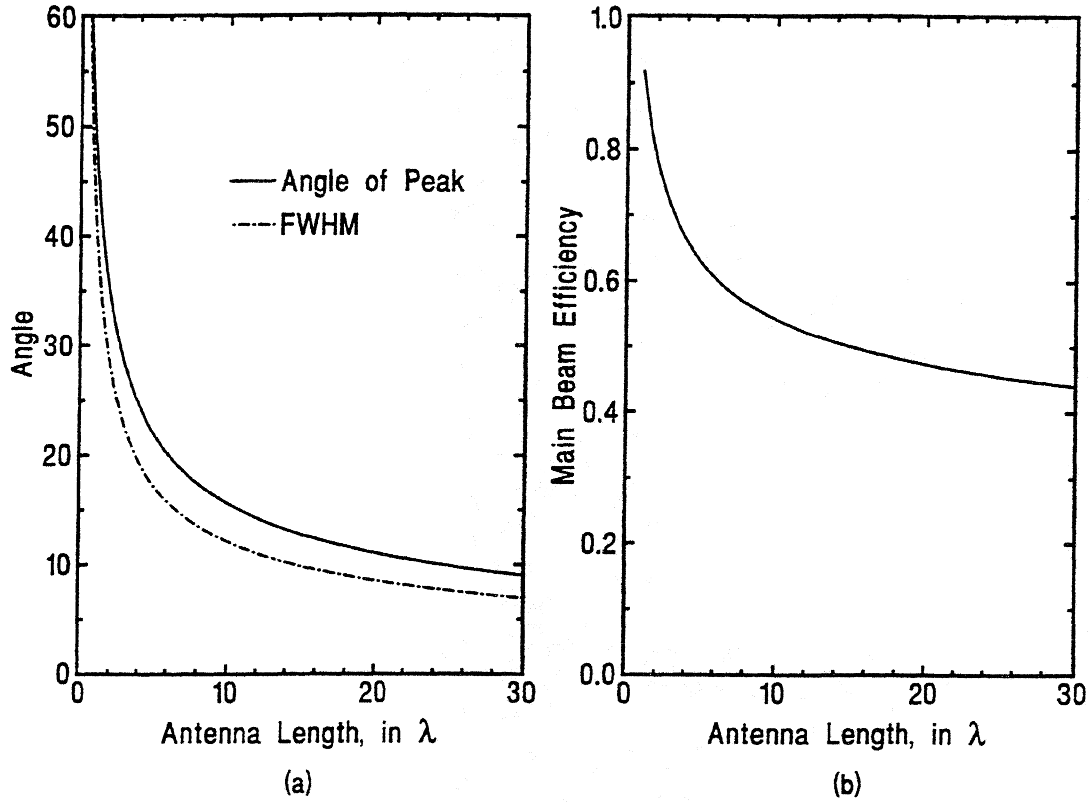

Figure 1: Peak angle, width, and efficiency of a long wire antenna

The apex spacing s increases slowly with antenna length, as will be shown later, and for this reason we still need to be careful about dimensional tolerances for the short wavelength mixers. A $25\,\lambda$ mixer for $63\,\mu$m, for example, will have an apex spacing $s = 3\,\lambda$, which is $189\,\mu$m. For best operation this distance should be accurate to $\lambda/2$, which is 16% of s.

(B) Mixer Description

The discussion which follows is adapted from Zmuidzinas *et al.* [5], with emphasis on the parameters of antennas with lengths of 20-30 λ.

(1) Long Wire Antennas

The antenna's radiation pattern is that of a long wire with a traveling-wave excitation. For such an antenna (assuming equal current and phase velocities) the far-field pattern is given by:

$$E_\theta(\theta) \propto \sin\theta \left[\frac{\sin[(\pi L/\lambda)(1-\cos\theta)]}{(piL/\lambda)(1-\cos\theta)}\right], \quad (1)$$

where L/λ is the length of the wire in wavelengths and θ is the angle between the wire and the direction of peak radiation. If there are no obstructions, the radiation pattern is symmetric about the wire axis (independent of the azimuthal angle ϕ). The power radiated by the long wire antenna can be computed from the square of the E-field given in the equation above. The intensity in the higher order lobes dies away because of the $\sin^2\theta$ term in the power dependence, and is exactly zero by $\theta = 180°$. We are interested in the fundamental lobe of the response. For antennas with lengths $\geq 4\,\lambda$, the angle θ_{max} at which the response is maximized is given approximately by:

$$\theta_{max} \approx \cos^{-1}(1 - 0.37101\,(\lambda/L)), \quad (2)$$

where L is the length of the antenna. Figure 1a illustrates this equation and also shows the 3 dB beamwidth as a function of antenna length. Figure 1b shows the fraction of the total power radiated (or received) in the main lobe as a function of L/λ (where the integral around the symmetry axis of the antenna has been performed). As we go to longer antennas, the power in the main lobe drops, but not rapidly. As can be seen in Figure 1b, a $25\,\lambda$ wire is 70% as efficient as a $4\,\lambda$ wire in coupling power into the fundamental lobe, and therefore is quite attractive for work at the shortest wavelengths. From these graphs we can deduce three things: (1) antenna lengths of 4-30 λ have nominally similar efficiencies, (2) antenna lengths can be chosen to synthesize a beamwidth well matched to the telescope optics, and (3) the beam angle and width of the antenna response is approximately proportional to $\sqrt{\lambda/L}$ and hence not a strong function of the antenna length for $L > 10\,\lambda$.

(2) Corner Reflectors

The placement of the corner reflector in the path of an incoming beam will produce standing waves in the vicinity of the reflector. For optimum coupling, the antenna should be located at the first standing-wave peak produced by radiation incident on the symmetry axis of the corner reflector ($\phi = \pi/4$) and at the angle θ_{max}. For the specific case of a 90° corner reflector, the optimum spacing s of the antenna to the reflector apex is given by:

$$s = \lambda/2 \sin\theta_{max} \ . \qquad (3)$$

This equation is plotted in Figure 2, where θ_{max} is solved for exactly and not by the approximation given before. From the figure we see that for a $4\,\lambda$ antenna $s = 1.2\,\lambda$, whereas for a $25\,\lambda$ wire $s = 3\,\lambda$.

Figure 3 shows the calculated E-plane beam patterns (in the plane of the antenna wire and reflector apex) for $4\,\lambda$ and $30\,\lambda$ mixers with the corner reflector in place. The increased sidelobe content of the longer wire is evident, but the main-beam response is well formed in both cases. The cross-power (H-plane) response has a similar beamwidth and is free

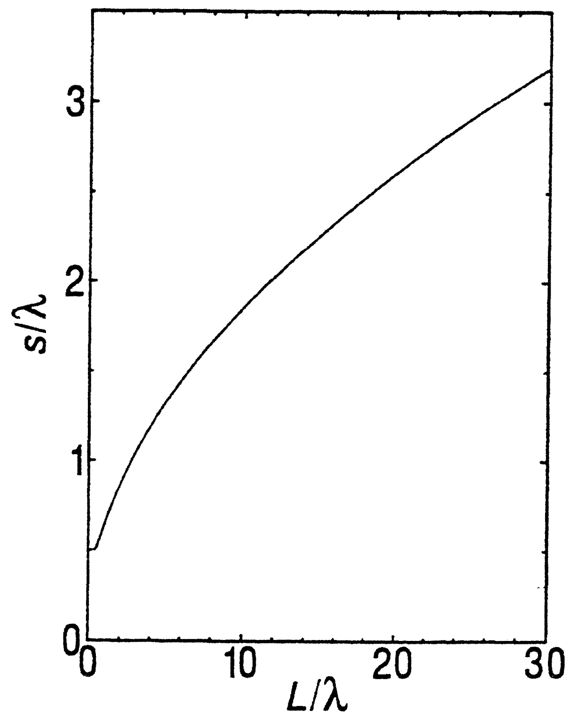

Figure 2: Optimum reflector spacing s as a function of antenna length L

of sidelobe structure for $\theta = \theta_{max}$. The off-axis response, on the other hand, contains considerable sidelobe structure, but nothing larger than −6 dB relative to the peak response. The mixer beamwidths are slightly smaller than those of long-wire antennas in free space because of the interaction of the reflectors. Notice that some low level E-plane sidelobes of a free-space antenna are significantly reduced after the reflectors are positioned. Our measurements of beam patterns for 4 and $9.7\,\lambda$ mixers confirm these predicted response patterns, and give us confidence that the 20-30 λ mixers will perform to expectations. Our first measurements for the E-plane response of a mixer with a $25.2\,\lambda$ antenna are shown in Figure 4, along with the calculated (smooth curve) values. These measurements were done at $\lambda = 86$ μm (3.5 THz), because the particular mount used could not be ad-

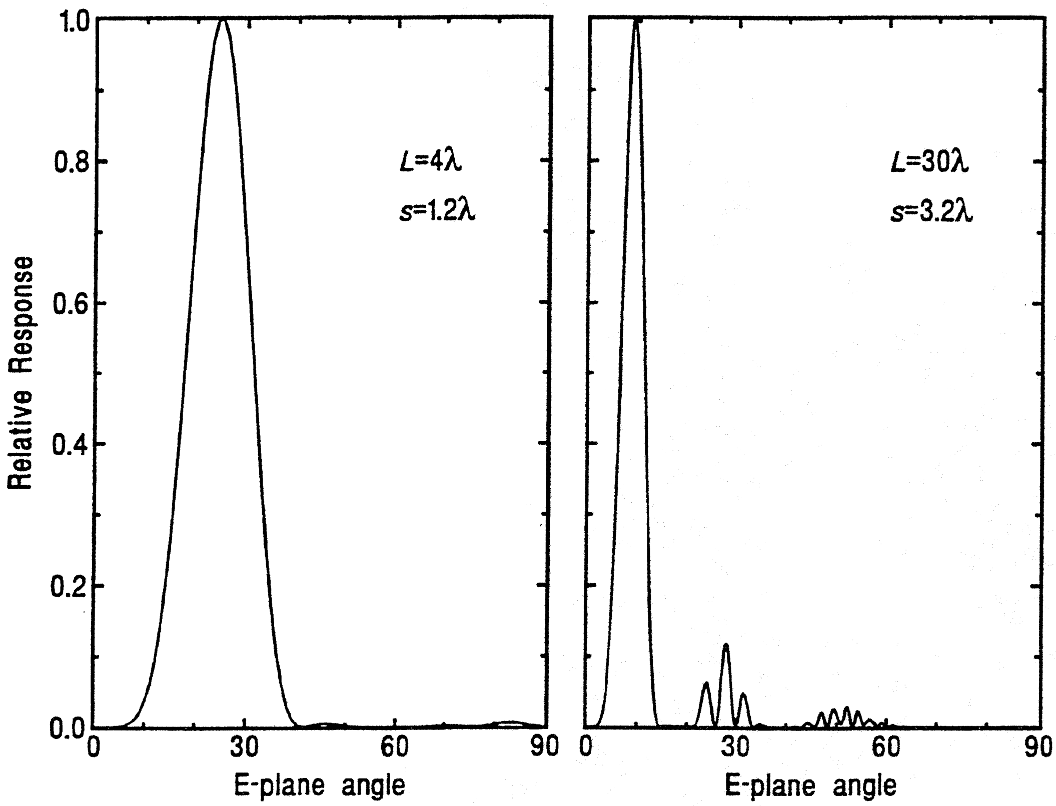

Figure 3: E-plane beam patterns for 4 λ and 30 λ antennas with optimally spaced corner reflectors

justed for shorter wavelengths. The excess response measured at 30° is thought to be the result of the observed tilt of the antenna whisker relative to the apex line of the corner reflector, and can be improved with further work. Regardless, the agreement between the measured and calculated responses of the mixer in the vicinity of the main lobe is quite good.

(C) Sensitivity Measurements

Our experience with mixers with antenna lengths between 4 and 10 λ leads us to expect receiver noise temperatures <5000 K (DSB)/THz between 2.5 and 5 THz. Although we have achieved a receiver noise temperature of 5000 K (DSB) at 1.9 THz (C II line), our best noise temperature at 2.53 THz (118 μm) was 12,000 K (DSB) 2 years ago with cooled 1T11 and 1T15 Schottky devices from the Univ. of Virginia Semiconductor Device Lab. It seems that cooled devices with anode sizes <0.4 μm (and concomitant R_S values of 30-40 ohms at room temperature) show an increase in R_S upon cooling that limits the coupling efficiency into a 50 ohm IF amplifier.

The mixer of Figure 4 produced a system noise temperature of 15,000 K (DSB) at 3.5 THz (86 μm). The mixer uses a type 1T15 GaAs Schottky diode and was tested at room temperature, but the 6 GHz IF amplifier was cooled to 77 K where it achieves $T_N = 35$ K. (Note that 6 GHz is the IF needed for observations of the oxygen line at 63 μm with the fixed frequency of the laser LO line.) No data are currently available on conversion loss, but measurements are continuing, especially at 4.75 THz (63 μm) where our goal is $T_{sys} = 25,000$ K (DSB). This modest performance will be more than adequate to yield S/N ratios better than 100 on many sources of the interstellar 63 μm O I line.

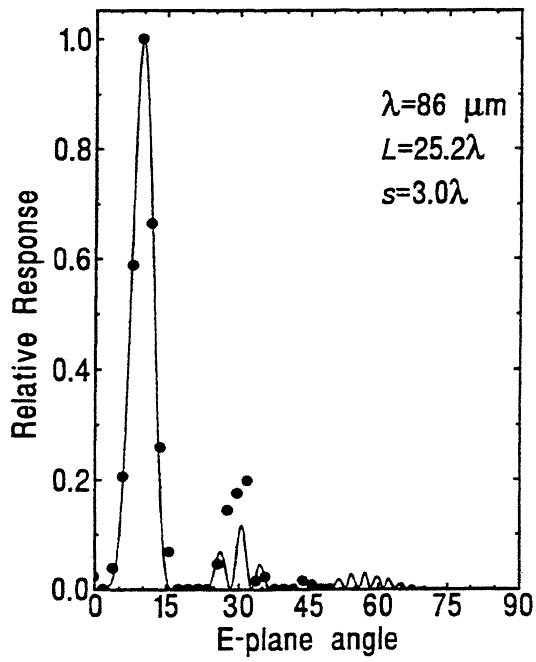

Figure 4: Calculated and measured E-plane response of a 25.2 λ antenna with optimally spaced reflectors

References

[1] Boreiko, R. T. and Betz, A. L., "Heterodyne Spectroscopy of the J=22-21 CO Line in Orion", *Ap. J. (Letters)*, **346**, L97-L100 (1989).

[2] Boreiko, R. T., Betz, A. L., and Zmuidzinas, J., "Heterodyne Spectroscopy of the 158 Micron C II Line in M42", *Ap. J. (Letters)*, **325**, L47-L51 (1988).

[3] Kräutle, H., Sauter, E., and Schultz, G. V., "Antenna Characteristics of Whisker Diodes Used as Submillimeter Receivers", *Infrared Physics*, **17**, 477-483 (1977).

[4] Grossman, E. N., "The Coupling of Submillimeter Corner-Cube Antennas to Gaussian Beams", *Infrared Physics*, **29**, 875-885 (1989).

[5] Zmuidzinas, J., Betz. A. L., and Boreiko, R. T., "A Corner-Reflector Mixer Mount for Far-Infrared Wavelengths", *Infrared Physics*, **29**, 119-131 (1989).