A 15 ELEMENT IMAGING ARRAY FOR 100 GHZ

N.R. Erickson, P.F. Goldsmith, C.R. Predmore, G.A. Novak and P.J. Viscuso

Five College Radio Astronomy Observatory
Department of Physics and Astronomy
University of Massachusetts
Amherst, MA. 01003

ABSTRACT

A focal plane imaging array receiver is described which covers the 90–115 GHz range for radio astronomical observations. The 3x5 array uses cryogenic Schottky diode mixers with integrated HEMT IF amplifiers. A cold quasi–optical filter selects the correct sideband, and terminates the image at 20 K. Polarization interleaving is used to minimize the array size on the sky.

INTRODUCTION

As astronomical millimeter–wave receiver systems improve in performance, their overall system noise temperature becomes increasingly dominated by atmospheric emission and absorption. The only practical method of increasing the data rate for spatially extended sources is to construct imaging arrays. Here we describe a 15 element imaging array receiver which is nearly complete at the FCRAO. This system is intended for astronomical spectral line observations with the 14m radio telescope over the frequency range 90 to 115 GHz. The array operates single sideband, with fixed tuned mixers. This is the first fully integrated millimeter–wave array receiver and also the first millimeter receiver to make extensive use of cooled optics.

MIXERS AND IF AMPLIFIERS

Schottky diode mixers operated at a temperature of 20 K have been chosen over SIS mixers for this project because of the large number and the need to minimize the complexity of operation. In particular 20 K operation and the relative ease of use of Schottky diode mixers have a substantial advantage in a system such as this. Each mixer uses a fairly conventional reduced height waveguide mount similar to an earlier FCRAO design (1), but with a fixed tuned backshort since individual tuning is impractical for an array. The internal waveguide is 0.25 x 2.3 mm and is converted to full height with a two step transformer. A cross section of the mixer and amplifier is shown in Fig. 1. Mixer diodes are from the University of Virginia (batch 2I1–150) and have a capacitance of 4.5 fF, a series resistance of 15 Ω, and doping optimized for cryogenic operation. This low capacitance permits a wide band to be covered with a fixed backshort, and also reduces the LO power required. The measured LO power for these mixers at 20 K is 20 μW while the mixer noise temperature varies from 50 to 90 K DSB over the range of mixers and the operating band.

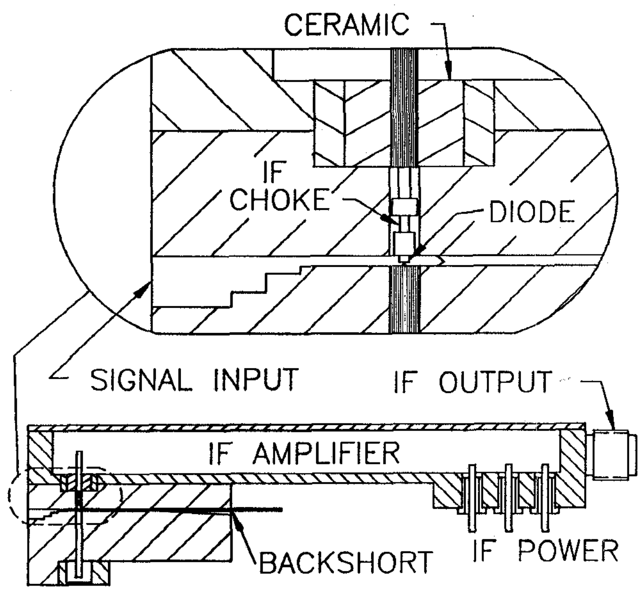

Fig. 1. Cross section of the mixer and IF amplifier.

The IF is centered at 1450 MHz with a required bandwidth of 320 MHz, set by the bandwidth of the filter backends. The amplifier uses a HEMT input stage followed by two conventional FET stages and is integrated into the mixer block with noise and impedance matching directly to the mixer IF impedance (500 Ω at the diode). In this way it is not necessary to individually match the amplifier and mixer to 50 Ω, and much flatter and more stable noise and gain may be achieved. The amplifiers are tuned up using a special fixture which converts a 50 Ω load into a replica of the mixer output impedance across the IF band. Thus all the amplifier testing can be done using standard equipment. Due to the small space available for the amplifier, all matching is done with lumped inductors. The typical amplifier noise temperature is 4 K at 20 K physical temperature. The gain is greater than 30 dB including a 10 dB attenuator on the output to ensure stability. Bias is via an internal resistor network so that all amplifiers can operate from a common power supply. The mixer and amplifier together have a cross section of 2.0 cm square so that they may be packed closely together.

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FEED HORNS

Corrugated feed horns have excellent beam efficiency, but because they are round and require a fairly thick wall (for the grooves), they do not pack together closely. However we have determined that the packing in a rectangular array can be significantly improved by cutting away flat sections from the sides of the horns, reducing the size to 88% of the initial diameter. This cutaway makes possible the arrangement shown in Fig. 2, and produces only a small increase in beam size. The horn size chosen with a taper length of 8.9 cm and an OD of 2.3 cm, was measured after cutting its aperture down to 2.0 cm across the flats. Initially the waist radius of the best fit Gaussian beam was 0.66 cm at 85 GHz, decreasing to 0.60 cm at 115 GHz. After cutting, the waist radius was a constant 0.60 cm over this band. The quality of the beam pattern is essentially unchanged. The horn length scales as the square of the aperture so the aperture was chosen as small as possible to minimize the feedhorn mass. The final limitation was the cross section of the mixer itself, which can be no bigger than the horn. The circular waveguide in the horn is converted to rectangular using a two step mode transition.

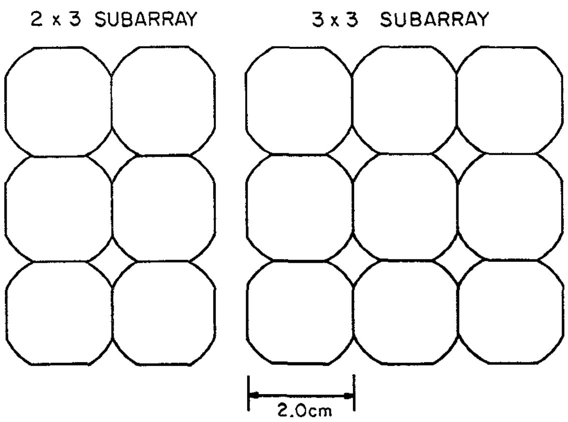

Fig. 2. Feed horn layout. The gap between horns allows for interleaving.

OPTICS

The optical system performs three critical functions, sideband filtering, polarization interleaving on the sky and reduction of the feed horn cluster size, which together produce a rather complex appearing design. The overall dewar optics layout is shown in Fig. 3.

A single-sideband filter is required to eliminate the image response for well calibrated spectroscopy, and to terminate this image at a low temperature to achieve the minimum receiver noise temperature. The sideband filter in this system uses a new type of polarizing interferometer (2) developed specifically for this application, and shown schematically in Fig. 4. It consists of a pair of fused silica wedges ~1.2 cm thick in total which are metallized on the back and have a wire grid on the front at 45° to the incident field. The device behaves as a very thick wave plate in reflection, and can be tuned so that the signal

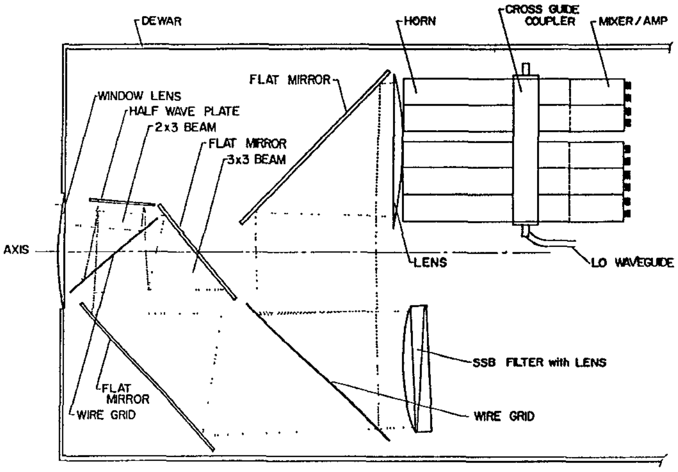

Fig. 3. Optics layout in the dewar. Image loads are below the mixer feeds.

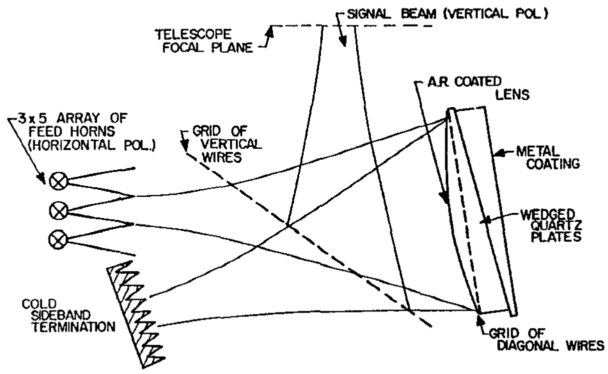

Fig. 4. Reflective polarizing interferometer used as a sideband filter. Optics shown are similar to the array optics but are simplified for clarity.

frequency is reflected in one linear polarization and the image in the other. Tuning this filter is accomplished by sliding the wedges over each other, thus changing the effective thickness. For the most compact optics, the feed horns are all aimed at the center of the filter by a lens covering the entire cluster. A second lens is placed in contact with the front of the filter to provide collimation of the beam internal to the filter. A third lens (serving as the dewar window) accepts the diverging beams leaving the filter and restores them to parallelism on the outside of the dewar. Due to the dielectric filling within the sideband filter, a single filter can handle all array elements without excessive angle tuning effects. This filter and the image band termination operate at a temperature of 20 K. The other system optical elements are cooled to 80 K.

To produce a more compact array on the sky, and to reduce the dewar window size, polarization diplexing is used to interleave 6 of the beams between positions of the other 9. This combining is done with a system of mirrors and wire grids near the input beam waist. Traveling outward from the mixers, the 2x3 group becomes well separated from the 3x3 group at this point. This separation is increased by the gap between the two groups of mixers, so that the diplexing produces little beam truncation. The 3x3 group has its polarization unchanged, while the 2x3 group has its polarization rotated 90° by a reflective half-wave plate. This second group is then laterally offset and combined with the first using a wire grid. The optical alignment has been measured to produce nearly exactly the predicted beam spacing.

Finally, also as a result of the three lenses mentioned above, the internal array size is magnified by a factor of 1.35, and the effective focal plane is displaced to a point 5 cm inside the dewar window. This magnification significantly reduces the size of the cold feed horn cluster, and thus the size of the dewar. The two cold lenses are made of boron nitride (3), a low loss machinable ceramic with $\epsilon = 2.05$. The surfaces of these lenses are impedance matched with $\lambda/4$ layers of expanded teflon fabric (4) laminated with epoxy resin. This combination survives thermal cycling well, and provides an excellent match. The dewar window lens is made of fused silica, with matching coatings of polyethylene.

The beam spacing on the sky will be 50 arc sec between interleaved polarizations and 100 arc sec between rows, as shown in Fig. 5. The FCRAO 14 m telescope has a FWHM beam width at 105 GHz of 50 arc sec.

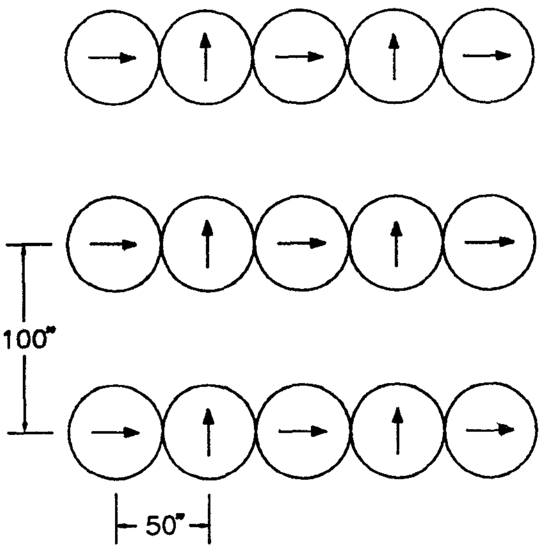

Fig. 5. Array beams on the sky, with half power beam width at 105 GHz. Polarizations are shown by arrows.

LOCAL OSCILLATOR

The local oscillator system is designed to be entirely computer controlled, with a minimum number of mechanical adjustments and with no chance of an incorrect frequency setting. To inject the LO into the mixers without any tuning, a multiport crossguide coupler is used. This consists of a single main line for the LO and a series of 15 cross guides to the mixers, each designed for minimum signal insertion loss (<0.2 dB) and 22–24 dB LO coupling across the band. While such a coupler is inefficient for a single mixer, in this case 6–9% of the input power is actually delivered to the mixers. The coupler uses full height waveguide for the signal lines and 1/2 height guide for the long LO line. Coupling is via one or three round holes depending on the coupling needed. The reduced height in one waveguide helps maintain a much flatter and stronger coupling than could be achieved otherwise. The required LO power at each mixer may be met by an input power of 4 mW to the coupler. The insertion loss of the coupler between the first and fifteenth port for the LO path is about 4.5 dB, and thus requires a continuous increase in coupling with length along the coupler.

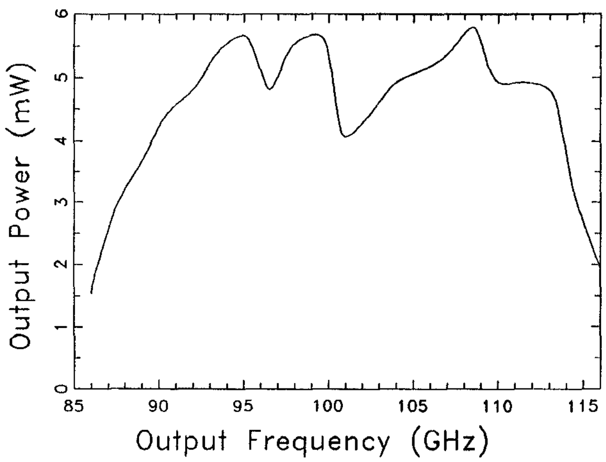

Fig. 6. Output of the complete local oscillator chain, with tripler fixed tuned, operating at a temperature of 77 K.

The LO is a phase locked YIG tuned FET oscillator in the 29–38 GHz range driving a 90 mW power amplifier. This is followed by a fixed tuned frequency tripler at 20 K mounted close to the LO coupler. The tripler uses a varactor diode with $C_j(0) = 29$ fF, $R_s = 10\ \Omega$ and $V_b = 21$ V (Univ. of Va. type 8P3). This tripler is designed to permit a good input and output match over the full band of operation with no mechanical tuning. Varactor multipliers work well at low temperatures and for this device the output at 77 K is 0.7 dB greater than that obtained at room temperature. This system produces 4 mW minimum over 90–114 GHz, with usable power down to 88 GHz. Fig. 6 shows a plot of the tripler output at a constant bias voltage of 7 V. Due to the uniformity of the power over the band, and the relative insensitivity of the mixers to their LO drive, no LO level adjustment is needed. The power amplifier noise would add about 5–20 degrees to the mixer noise temperature if unfiltered. Its excess noise contribution is reduced to a negligible level by a room temperature mechanically tuned filter with 20 dB of rejection. In addition, the tripler produces some noise due to the higher temperature of the varactor and due to avalanche breakdown from the high drive level. This is reduced by a cold tunable filter on the output, having about 6 dB rejection.

GENERAL OPERATION

All of the cold components are mounted on a single optics plate measuring 33x48 cm , and mounted in a vacuum dewar 41 cm dia x 59 cm long. Cooling is provided by two 3.5 W, 20 K refrigerators. The dewar is mounted at the Cassagrain focus of an altitude–azimuth telescope and must rotate to maintain a fixed orientation as the telescope tracks an astronomical source. The dewar window is on the axis of this dewar so that the pointing of the array does not depend on rotation.

All functions are computer controlled including the three mechanical tuners needed. Mixer bias is set by 15 current sources which the computer can individually adjust for best operation, given the fixed LO power. The system is designed for remote observing and should make possible a number of new observing strategies due to its high data rate and frequency agility.

PERFORMANCE

While the system is not complete, most components and the optical elements have been tested individually. Fabrication of the amplifiers is in process and a cold test of the full system remains to be completed. The mixer/amplifiers have noise temperatures of 75–100 K DSB over the band. Optics losses have been measured and their contributions to the overall system may be estimated, including the image termination at 20 K. The result is an expected receiver noise of 230–290 K SSB over the 90–115 GHz range.

ACKNOWLEDGEMENT

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(2) N.R. Erickson, "A New Quasi–Optical Filter, the Reflective Polarizing Interferometer," *Int. J. IR and mm Waves*, vol 8, pp. 1015–1025.

(3) Combat boron nitride, grade HP, Standard Oil Engineered Materials Company, Amherst, NY.

(4) Gore–Tex fabric radome laminate, W.L. Gore and Associates, Elkton, MD.