Large Format Heterodyne Arrays for Terahertz Astronomy

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***Abstract*— For future ground, airborne and space based single aperture telescopes, multipixel heterodyne imaging arrays are necessary to take full advantage of platform lifetime, and facilitate science requiring wide field spectral line imaging. A first generation of heterodyne arrays with ~10 pixels has already been constructed, i.e. CHAMP, SMART, HERA, DesertStar, PoleStar and HARP. Our group is now constructing SuperCam, a 64 pixel heterodyne array for operation in the 350 GHz atmospheric window. This instrument will realize another order of magnitude increase in array pixel count. Several new techniques were used for SuperCam to maximize integration and modularity. Unlike other SIS array receivers, SuperCam is built around 8 pixel linear mixer modules, rather than independent mixer blocks. These modules house 8 single ended waveguide mixers with SOI substrate SIS devices. Each device is tab bonded to a MMIC based LNA. These modules dissipate only 8 mW of heat, while still maintaining 5 K IF noise temperature and 32 dB gain. Blind mate IF and DC connectors allow each module to be inserted in or removed from the focal plane as a unit. The modules are machined using a state-of-the-art CNC micromilling machine acquired specifically for this project. IF signals are processed by 8 channel IF downconverter boards, which provide gain, baseband downconversion and IF total power monitoring. A real-time FFT spectrometer implemented with high speed ADCs and Xilinx 4 FPGAs produce spectra of the central 250 MHz of each channel at 0.25 km/s spectral resolution. For arrays with an additional order of magnitude increase in pixel count, several additional technical problems must be overcome. Kilopixel arrays will require advances in device fabrication, cryogenics, micromachining, IF processing and spectrometers. In addition, seemingly straightforward receiver systems will require new approaches to realize a kilopixel heterodyne array with manageable complexity and cost. Wire count and 4K heat load must all be reduced significantly compared to SuperCam. IF and DC cabling and interconnects may be replaced with multiconductor microstrip or stripline ribbon. Parallel biasing of LNAs, magnets and even SIS devices is feasible if device uniformity is good enough. IF processing will require further integration, possibly with integrated MMIC chips containing all parts of a IF downconversion chain. Continued advances in FFT spectrometers could allow processing many hundreds of gigahertz of IF bandwidth for a realizable cost. We present results from final SuperCam receiver integration and testing, and concepts for expanding heterodyne arrays to kilopixel scales in the future.**

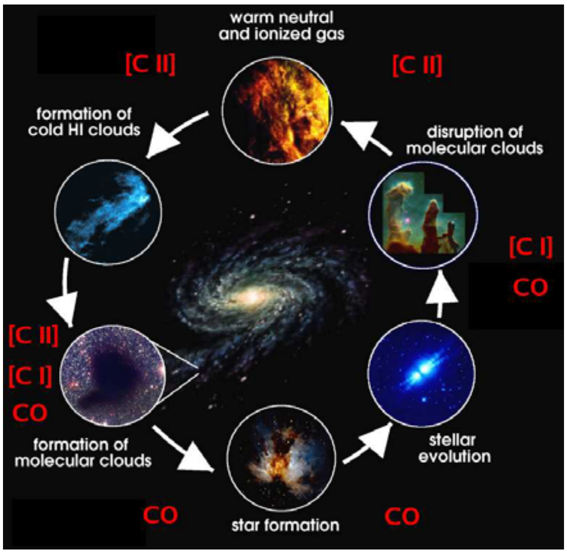

Figure 1: Life cycle of the ISM

I. INTRODUCTION

SuperCam has been designed to operate in the astrophysically rich 870μm atmospheric window. The Heinrich Hertz Submillimeter Telescope has a 13μm RMS surface, making it the most accurate large submillimeter telescope currently in operation. In addition, the 10,500ft elevation site on Mt. Graham offers weather sufficient for observing in this window more than 50% of the observing season, 24 hours per day. The receiver is an 8x8 array constructed from integrated 1x8 mixer modules, with state of the art mixer, local oscillator, low noise amplifier, cryogenic and digital signal processing technologies.

SuperCam will have several times more pixels than any existing spectroscopic imaging array at submillimeter wavelengths. The exceptional mapping speed that will result, combined with the efficiency and angular resolution provided by the HHT will make SuperCam a powerful instrument for probing the history of star formation in our Galaxy and nearby galaxies. SuperCam will be used to answer fundamental questions about the physics and chemistry of molecular clouds in the Galaxy and their direct relation to star and planet formation. Through Galactic surveys, particularly in CO and its isotopomers, the impact of Galactic environment on these phenomena will be realized. These studies will serve as “finder charts” for future focused research (e.g. with ALMA) and markedly improve the interpretation, and enhance the value of numerous contemporary surveys.

II. SUPERCAM SCIENCE

From the Milky Way to the highest-redshift protogalaxies at the onset of galaxy formation, the internal evolution of galaxies is defined by three principal ingredients that closely relate to their interstellar contents:

- The transformation of neutral, molecular gas clouds into stars and star clusters (star formation).
- the interaction of the interstellar medium (ISM) with the young stars that are born from it, a regulator of further star formation.
- the return of enriched stellar material to the ISM by stellar death, eventually to form future generations of stars.

The evolution of the stellar population of galaxies is therefore determined to a large extent by the life cycles of interstellar clouds: their creation, starforming properties, and subsequent destruction by the nascent stars they spawn. The life cycle of interstellar clouds is summarized pictorially in Figure 1. Although these clouds are largely comprised of neutral hydrogen in both atomic and molecular form and atomic helium, these species are notoriously difficult to detect under typical interstellar conditions. Atomic hydrogen is detectable in cold clouds via the 21 cm spin-flip transition at 1420 MHz, but because the emission line is insensitive to gas density, cold (T~70K) atomic clouds are not distinguishable from the warm (T~8000K) neutral medium that pervades the Galaxy. Furthermore, neither atomic helium nor molecular hydrogen (H_2) have accessible emission line spectra in the prevailing physical conditions in cold interstellar clouds. Thus, it is generally necessary to probe the nature of the ISM via rarer trace elements. Carbon, for example, is found in ionized form (C^+) in neutral HI clouds, eventually becoming atomic (C), then molecular as carbon monoxide (CO) in dark molecular clouds. The dominant ionization state(s) of carbon accompany each stage of a cloud's life in Figure 1. In general, however, only global properties can be gleaned from the coarse spatial resolution offered by studies of external galaxies. Therefore detailed interstellar studies of the widely varying conditions in our own Milky Way Galaxy serve as a crucial diagnostic template or “Rosetta Stone” that can be used to translate the global properties of distant galaxies into reliable estimators of star formation rate and state of the ISM.

SuperCam has been designed to complete a key project Galactic plane survey in the ^{12}CO(3-2) and ^{13}CO(3-2) transitions of carbon monoxide. This survey, covering 500 square degrees of the Galaxy including a fully sampled survey from l=0º-90º and -1º<b<1º in addition to many molecular cloud complexes visible from the northern hemisphere, will improve the spatial resolution of existing surveys by more than a factor of 10. In addition, this will be the first submillimeter CO Galactic plane survey, providing a census of molecular gas actively participating in star formation. When combined with existing CO(1-0) surveys, a complete excitation temperature map of the survey region can be constructed. The depth of the survey is sufficient to detect CO to a level consistent with A_v~1, detecting all CO that has formed in-situ.

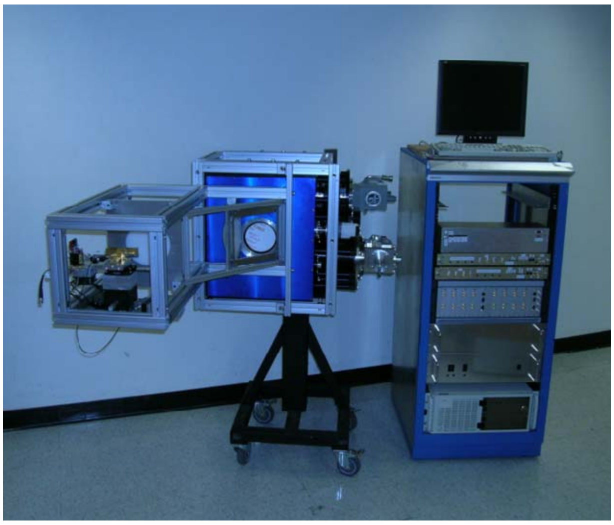

Figure 2: The SuperCam cryostat, LO optics and support electronics.

III. SUPERCAM INSTRUMENT DESCRIPTION

A. *Instrument Design*

In the past, all heterodyne focal plane arrays have been constructed using discrete mixers, arrayed in the focal plane. SuperCam reduces cryogenic and mechanical complexity by integrating multiple mixers and amplifiers into a single array module with a single set of DC and IF connectors. Well conceived, efficient packaging is essential to the successful implementation of large format systems. The enormous complexity of even a small discrete system suggests a more integrated approach for larger systems. At the heart of the array is an 8 pixel linear integrated array of low-noise mixers. The array mixer contains first stage, low-noise, MMIC IF amplifier modules with integrated bias tees. Eight of these modules are then stacked to produce the final 64 pixel array.

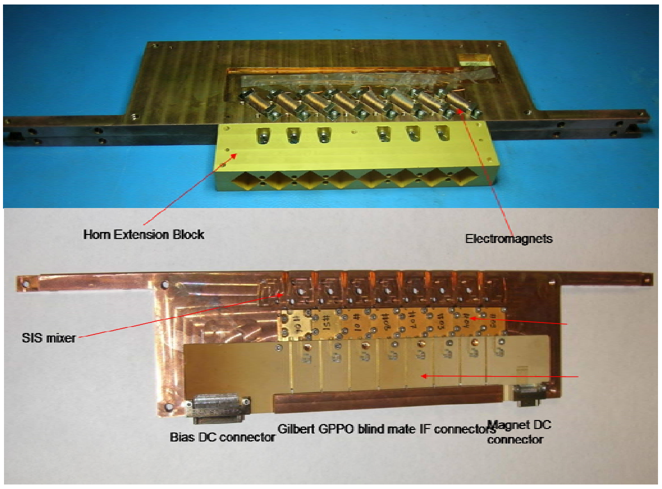

Figure 3: A completed SuperCam 1x8 mixer module, fully assembled (top) and with the top cover removed (bottom).

B. Cryogenics

The SuperCam systen with attached LO optics, frontend support electronics and backend electronics is shown in Figure 2. The cryostat was constructed by Universal Cryogenics in Tucson, Arizona, USA. Light from the telescope enters the cryostat through a 150 mm diameter AR coated, crystalline quartz vacuum window and passes through a GoreTex GR IR blocking filter on the 40 K radiation shield before illuminating the 4 K mixer array. SuperCam uses a Sumitomo SRDK-415D cryocooler. The cooler has 1.5 W of thermal capacity at 4.2 K and 45W at 40K with orientation-independent operation. The operating temperature of the cryocooler is stabilized by the addition of a helium gas pot on the 2nd stage. A CTI cryogenics CTI-350 coldhead supplements the cooling of the 40K shield, and provides 12K heatsinking for the 64 stainless steel semi-rigid IF cables. The addition of this second coldhead permits the use of moderate lengths of standard coaxial cable while maintaining low heat load at 4K. Annealed and gold plated copper straps with a flex link connect the 4K cold tip to the cold plate, with less than an 0.25K temperature differential. Tests using heaters on the 4K cold plate, and system tests using prototype 1x8 mixer modules demonstrate adequate performance of the cryogenic system with the expected heat load from all 64 pixels.

C. Mixer Array

The SuperCam 64 beam focal plane is constructed from eight linear array modules with eight pixels each. Each pixel consists of a sensitive single ended SIS mixer optimized for operation from 320-380 GHz. The array mixers utilize SIS devices fabricated on Silicon-On-Insulator (SOI) substrates, with beam lead supports and electrical contacts. The waveguide probe and SIS junction are based on an asymmetric probe design currently in use at the Caltech Submillimeter Observatory in their new facility 350 GHz receiver. The 1x8 mixer subarrays are constructed from tellurium copper using the splitblock technique. Stainless steel guide pins and screws are used to ensure proper alignment and good contact between parts. Figure 3 shows a photograph of a prototype tellurium copper 1x8 mixer array fabricated at the University of Arizona using a Kern MMP micromilling machine. This block meets all design specifications, with 3 µm dimensional accuracy for all waveguide circuits. A diagonal feedhorn extension block is bolted to the front of the mixer array assembly, extending the diagonal horns to 11mm aperture size. This eliminates the

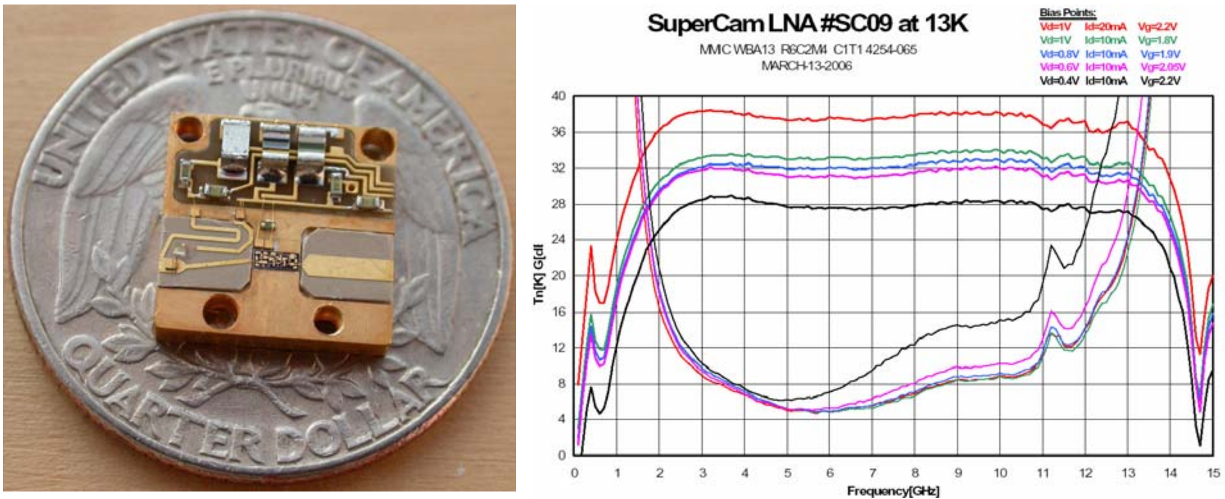

Figure 4: A SuperCam MMIC amplifier module, and typical measured results at 13K bath temperature for several bias points. Amplifier noise remains low for bias powers as low as 6 mW. Gain remains above 30 dB.

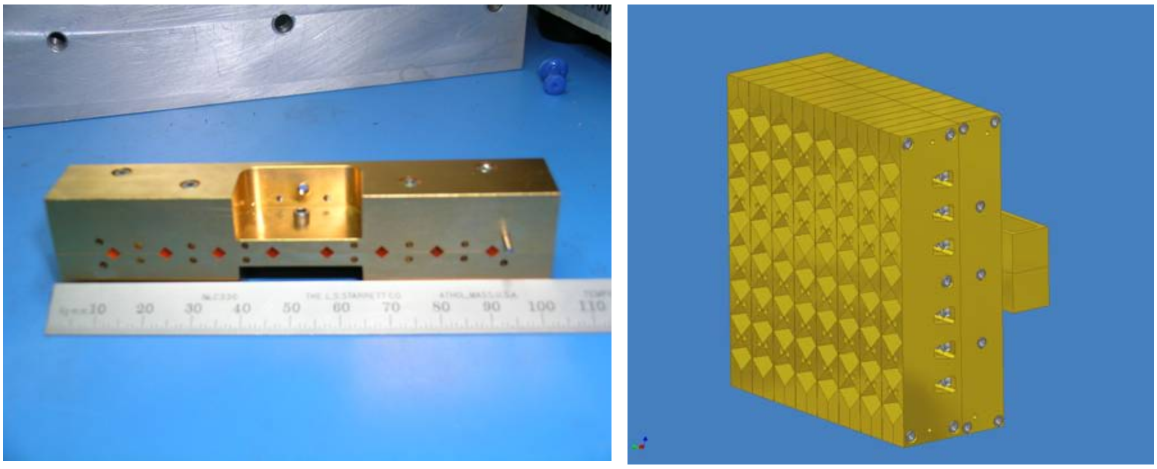

Figure 5: SuperCam prototype 8-way LO power divider (right), and solid model of the 64 way power divider now under construction. The divider is based on a corporate array of E-plane y-splitters, with waveguide twists on the output of the first module, and diagonal feedhorns on the output of the final 8 modules.

need for dielectric lenses and their associated manufacturing and alignment difficulties. The energy in the horn passes through a 90° waveguide bend before reaching the device. The waveguide environment is designed around full height rectangular waveguide, with a fixed quarter wave backshort. The SIS device is suspended and self-aligned above the suspended stripline channel via eight small beamlead supports. Both the hot and ground beamleads are tack-bonded with a wirebonder to the MMIC module (figure 4) input pad and block, respectively. The mixer blocks are fabricated at the University of Arizona using a Kern MMP micromilling machine purchased for this project. This numerically controlled mill can fabricate structures to micron accuracy with a high level of automation. A SuperCam 1x8 module can be produced in ~8 hours of machine run time, using only a single set of micro end mills per block half. The machine's 24 position tool changer allows a complete block to be fabricated with minimal user intervention during the machining process. Integrated workpiece and tool metrology systems, along with sophisticated computer aided manufacturing (CAM) software result in high part yield. Verification of fabricated parts though a high precision measurement microscope and 3D interferometric microscope insure dimensional accuracy and waveguide surface finish are within design tolerance. Testing, described in section 4, has been carried out using a single-pixel version of the SuperCam mixer design in a test cryostat, and with a full 8-pixel prototype mixer module. Series production of the final mixer modules is now underway.

D. *Local Oscillator*

With an array receiver, LO power must be efficiently distributed among pixels. Depending on the mechanical and optical constraints of the array, a balanced distribution can be achieved using quasioptical techniques or waveguide injection. With the quasioptical approach, dielectric beam splitters or holographic phase gratings are used to divide the LO energy between array pixels. The quasioptical approach works well for modest sized arrays. However, for the large format system being proposed here, the size of the required quasi-optical power splitter and diplexer become prohibitive. Therefore we have chosen to use a hybrid waveguide/quasioptical LO power injection scheme. The LO power for the array will be provided by a single solid-state, synthesizer-driven source from Virginia Diode Inc. The active multiplier chain consists of a high power solid-state amplifier followed by a series of tunerless broadband multipliers. The output of the multiplier is coupled to an eight-way waveguide corporate power divider with splitblock machineable waveguide twists. Each of the eight outputs provides the drive power for a 1x8 subarray via an identical 8 way corporate divider with diagonal waveguide feedhorn outputs. Figure 5 shows a prototype 1x8 power divider designed to power a single 1x8 mixer row. This power divider has been used in system tests with the prototype 1x8 mixer array and LO optics, with excellent results. Power balance was measured using a Thomas Keating power meter,

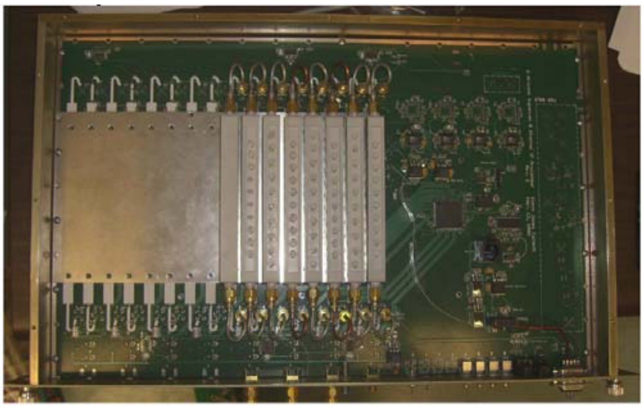

Figure 6: The inside of a SuperCam IF processor. This module provides amplification, programmable attenuation, passband filtering and total power detection for 8 channels.

and showed equal power balance within measurement errors, and ~1dB loss. The final 64 way power divider (CAD model shown in figure 5) is now under construction. An extended diagonal horn array similar to the mixer horn extension blocks then matches the LO beams to the mixers through a Gaussian beam telescope comprised of two large dielectric lenses. A 0.5 mil Mylar beamsplitter is used to inject the LO power. Testing has shown that a 2mW LO source is sufficient to optimally pump a 1x8 mixer array with this scheme, running at only ~20% of the maximum power output. An already purchased 12 mW source from Virginia Diodes will be more than sufficient to pump the final 64 puxel array, also with a 0.5 mil Mylar diplexer. This scheme ensures uniform LO power in each beam since the waveguide path lengths are identical for each beam. In addition, the waveguide feedhorns provide well controlled and predictable LO power distribution and coupling to each mixer. Accounting for conduction and surface roughness losses, we expect this 64-way network to add an additional 2dB of LO power loss compared to a lossless divider (double the measured loss of a single 8-way divider).

D. IF/Bias Distribution System

The IF outputs from the SIS devices are bonded directly to the input matching networks of low-noise, InP MMIC amplifier modules located in the array mixers. These amplifier modules have been designed and fabricated by Sander Weinreb's group at Caltech. The IF center frequency of the array is 5 GHz. The MMIC chip is contained in an 11mm x 11mm amplifier module that contains integrated bias tees for the SIS device and the amplifier chip. The module achieves noise temperature of ~5 K and delivers 32 dB of gain while consuming 8 mW of power. An example is shown in figure 4, with measured gain and noise data at 4 mW through 20 mW power dissipation. Noise remains virtually unchanged down to 6 mW power dissipation, while gain is reduced modestly. Several tests have been performed with these modules to ensure oscillation free operation, low noise, high stability, and no heating effects on the SIS device. Modules have been integrated into both single pixel and 1x8 array mixers, and have shown performance as good or better than expected with connectorized amplifiers. No heating effects are visible, although care must be taken to avoid oscillation due to feedback.

Figure 7: The SuperCam real time FFT spectrometer system, built by Omnisys AB. This single 3U crate can process 16 GHz of IF bandwidth at 250 kHz spatial resolution. It consumes less than 200W of AC power.

In addition to the LNA modules, the Caltech group has designed and constructed a warm IF system for SuperCam that will condition the IF signal for use with the SuperCam Array Spectrometer (figure 6). This IF system consists of a single large microwave printed circuit board with 8 channels of signal conditioning mounted in a modular chassis. The module contains a 5 GHz gain stage, switchable filters for both 250 MHz and 500 MHz bandwidth modes, baseband downconversion and baseband amplification.

E. Array Spectrometer

The SuperCam spectrometer delivers 64 channels at 250 MHz/channel with 250 kHz resolution, or 32 channels at 500 MHz with 250 kHz resolution. The system will be capable of resolving lines in all but the coldest clouds, while fully encompassing the Galactic rotation curve. The system is easily extendible to deliver 64 500 MHz bandwidth channels or 32 1 GHz bandwidth channels. This leap in spectrometer ability is driven by the rapid expansion in the capabilities of high speed Analog to Digital Converters (ADCs) and Field Programmable Gate Arrays (FPGAs). The SuperCam spectrometer, built by Omnisys AB of Sweden, is based on a real-time FFT architecture. High speed ADCs digitize the incoming RF signal at 8 bits resolution, preventing any significant data loss as with autocorrelation based schemes. Then, a large, high speed FPGA performs a real time FFT on the digitized signal and integrates the resulting spectrum. In our board architecture, 4 ADCs feed a single Xilinx Virtex 4 FPGA on each spectrometer board. Each board can process 4 500 MHz IF bandwidth signals or two 1 GHz IF bandwidth signals at 250 kHz resolution. Only recently has Xilinx released FPGAs fast enough and large enough to accommodate the firmware capable of this task. These systems are fully reconfigurable by loading new firmware

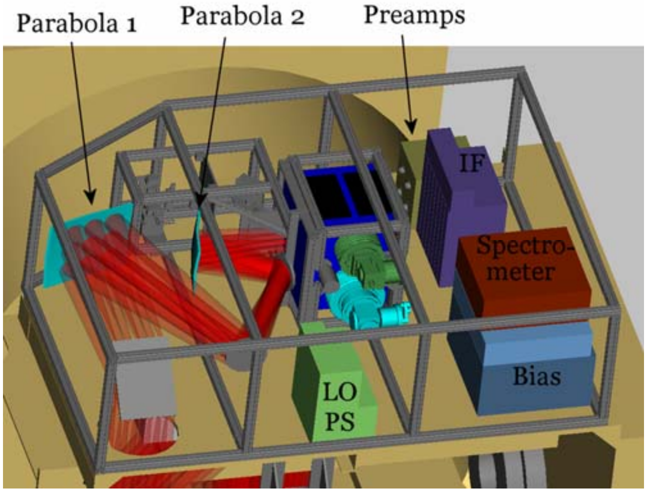

Figure 8: The SuperCam optics layout, mounted on the roof of the cassegrain cab of the HHT. This module contains the receiver front end, LO, optics and all electronics, and can be installed and removed as a pre-assembled unit.

into the FPGAs. In addition, the spectrometer can be easily expanded to increase bandwidth. We have received an 8 board system capable of processing 64x250 MHz, 32x 500 MHz or 16x1GHz IF signals (figure 7). In the 64x250 MHz mode, we power combine two IF signals into one spectrometer input. Stability testing shows the spectrometer is capable of delivering a spectroscopic Allan time in excess of 600s, including the effects of the IF processor described in section E.

F. Optics

The existing secondary mirror of the Heinrich Hertz Telescope provides a f/13.8 beam at the Nasmyth focus. The clear aperture available through the elevation bearing prevents the possibility of a large format array at this position. To efficiently illuminate a large format array like SuperCam, the telescope focus must fall within the apex room located just behind the primary. A system of flat mirrors directs the telescope beam through a hole in the roof of the apex room to the SuperCam system, mounted in a self-contained structure mounted on the roof. A system of re-imaging optics transforms the f number of the telescope to f/5. Since the physical separation between array elements in the instrument focal plane scales as 2fλ, lower f/#'s serve to reduce the overall size of the instrument. The reimaging optics are composed of two offset parabolas and several flat mirrors. All the reimaging optics can be mounted on a single optical frame. This frame can be completely constructed, aligned and tested off the telescope, then mounted as a complete unit. All electronics, including the backend, are located in this unit. The cryostat and optics frame have been designed using finite element analysis to minimize gravitational deflection, and the calculated deflections have been fed into the tolerancing of the optical design. The optical system was initially designed and optimized with Zemax, and was then verified by BRO research using their ASAP physical optics package. The system's efficiency exceeds 80% for all pixels, and has been verified to be robust to alignment and fabrication tolerances.

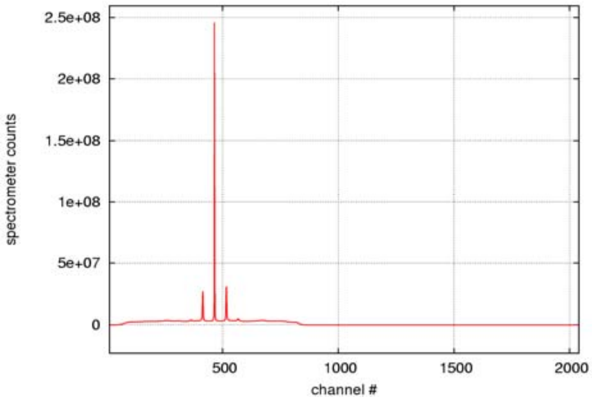

Figure 9: Spectrum from an end to end test of the SuperCam system.

IV. LABORATORY TESTING

For testing the SuperCam mixer design in the laboratory, we have designed two single pixel mixers. The first design uses an existing SIS junction design from the DesertStar 7-pixel array [7], but incorporates the Caltech designed MMIC module. This work has been reported in other papers [12,13]. We determined that the SIS receiver with integrated MMIC amplifier worked as well as a receiver with a separate

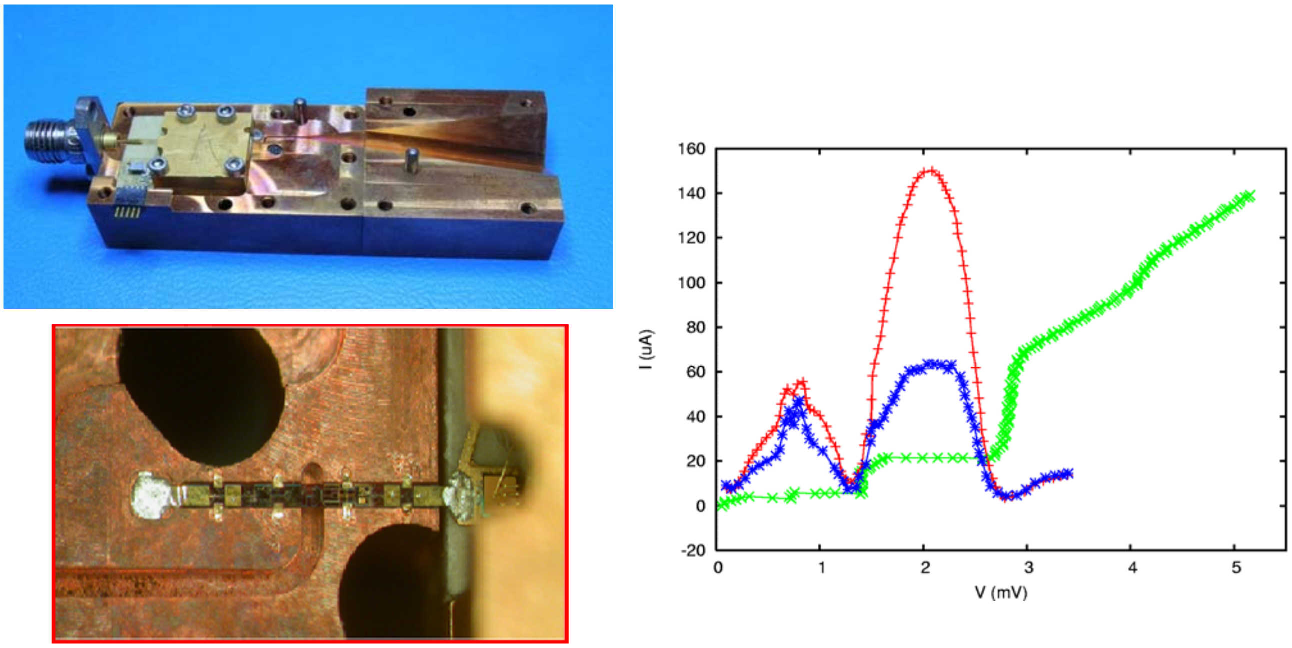

Figure 10: Single pixel test mixer with extended diagonal horn, LNA module and IF board (top left), a closeup of the SIS device (bottom left), and a representative IV curve and hot/cold total power curve (right).

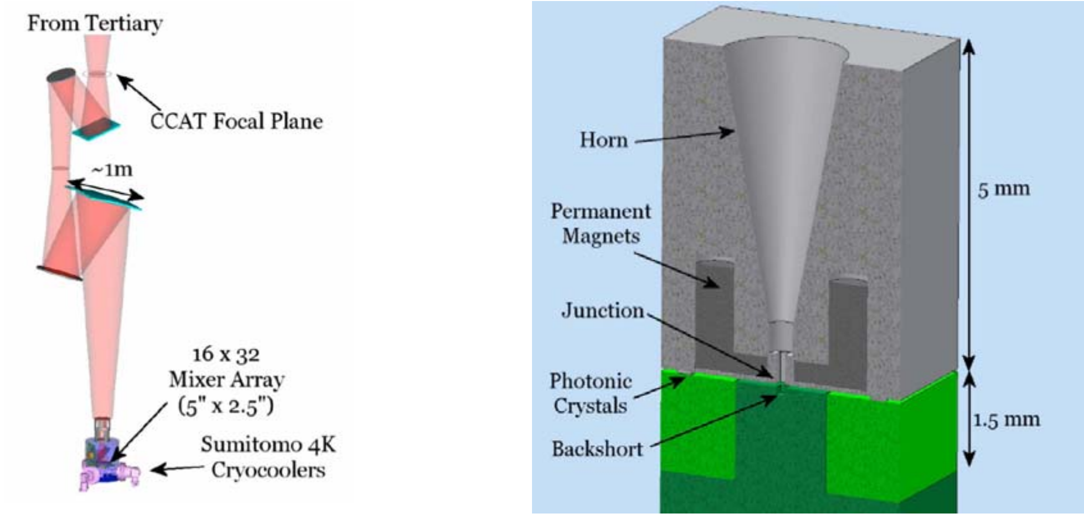

Figure 11: A concept for a 1024 pixel heterodyne array. The array consists of two 512 pixel subarrays, with polarization diplexing.

connectorized amplifier and cryogenic amplifier, and resulted in no heating effects at the SIS device from the close proximity of the amplifier. We later designed a second single pixel mixer that is an exact copy of a single pixel of the 1x8 mixer array design discussed in section 3.1.2. This mixer was designed to test the self-aligning beam-lead-on-SOI SIS devices that will be used in the SuperCam array, as well as the compact, low power electromagnet, MMIC amplifier module and extended diagonal feedhorn.

This mixer has been extensively tested for noise performance across the band, frequency response using a Fourier Transform Spectrometer, and stability measurements using the complete backend system. Tests with the latest wafer of SIS on SOI devices from UVa show close to optimal tuning, and measured noise temperatures of ~65 K with less than 10K variation across the measured band (LO limited to 330 to 365 GHz). Images of the single pixel mixer, a mounted SIS on SOI device and a representative IV and total power curve are shown in figure 10.

In addition, measurements of a prototype 1x8 mixer array has been completed using prototype or final electronics for the entire system. This mixer has been initially populated with devices from a less optimal wafer for system testing. These devices still deliver ~75K receiver noise temperature, but are not optimally tuned. The result of a full end to end test of this system is shown in figure 9. The sidebands around the line are the result of using a very high power LO source as a line injector. Even attenuated and pointed 180 degrees from the cryostat window, the power was still sufficient to generate harmonics in the IF processor.

V. NEXT GENERATION HETERODYNE ARRAYS

New ground based platforms for terahertz astronomy such as the 10m South Pole Telescope (SPT) and the 25m Cornell-Caltech Atacama Telescope (CCAT) require even larger heterodyne arrays to fulfill their scientific potential for diffraction limited imaging of large areas. Arrays of ~1000 pixels are desired for these applications, and will be vital for future space based single aperture terahertz experiments.

While SuperCam reduced cost and complexity though 1 dimensional integration of mixers into linear modules, kilopixel class arrays will require two dimensional integration into detector wafers to further reduce complexity and cost per element.

The design concept shown in figure 11 is based around 128 pixel SIS device cards, with microstrip or CPW contacts on two edges. These cards consist of SOI membrane on a thick Si carrier wafer. The carrier waver has deep RIE etched pockets behind each device to accept backshort pedestals. The SOI membrane spans the pedestal, suspending the device across the backshort. Four device cards are mosaiced to produce a 512 pixel array. A single 512 element backshort wafer would also be produced using deep RIE etching. Each pedestal would self align into the matching etched pocket in the device wafer. A fixed waveguide backshort on each pedestal would then complete the waveguide circuit. A single horn block, metal machined using drilled wideband conical horns would then be mounted above the silicon backshort wafer. Photonic crystal choke structures would allow a small gap between the device wafer and horn block, preventing stresses due to differences in material coefficient of thermal expansion (CTE) from breaking the device wafer. Permanent magnets embedded in this block would eliminate the need for biasing 1000 electromagnets.

Simple, single ended mixers have been chosen for this concept. While many advances in high performance sideband separating balanced mixers have been made, they are still mechanically complicated and would be very difficult to build into a 2D integrated focal plane. A sideband separating design with all necessary circuitry in a planar design on the device wafer would be compatible with 2-D integration.

DC bias could be phantom-fed through the IF lines from a ring shaped board around the device wafer. This board would also contain first stage IF amplification. More concentric boards, linked by wirebonds or flexible ribbon cable would contain additional IF amplification. Fiber transceivers, located at a warm stage in the cryostat, could output the IF signals on optical fiber rather than coaxial cables, vastly reducing the thermal load and cryogenic complexity of the instrument. Depending on device uniformity, parallel bias could be used to reduce the number of DC lines fed into the dewar. Alternatively, a custom ASIC could be produced to generate the bias signals inside the cryostat with only digital control fed into the cryostat.

Such an instrument would be only a few times larger than SuperCam, and could be cooled with only 2-3 1.5W 4K coolers.

Local oscillators capable of driving such a system using silicon etalon diplexers are already available for frequencies below 500 GHz and should be available on the timescale of such an instrument between 500 GHz and 1 THz. Both quasioptical and waveguide LO multiplexing schemes would be compatible.

Advances in digital signal processing promise to also make the backend system for such an array feasible. With higher speed ADCs, the IF processor for a kilopixel array could be completely eliminated. If the ADCs are fast enough to digitize the IF at it's native frequency, further downconversion is unnecessary. The next generation of real time FFT spectrometers is capable of delivering backend processing for costs of ~$5000 per gigahertz. A 1024 channel spectrometer with SuperCam's bandwidth per pixel could be built for a cost of $1-2M. On a 5-10 year timescale, several GHz per pixel at the $1M system cost level is feasible.

IV. CONCLUSION

We are constructing SuperCam, a 64-pixel heterodyne imaging spectrometer for the 870 μm atmospheric window. A key project for this instrument is a fully sampled Galactic plane survey covering over 500 square degrees of the Galactic plane and molecular cloud complexes. This ^{12}CO(3-2) and ^{13}CO(3-2) survey has the spatial (23") and spectral (0.25 km/s) resolution to disentangle the complex spatial and velocity structure of the Galaxy along each line of sight. SuperCam was designed to complete this survey in two observing seasons at the Heinrich Hertz Telescope, a project that would take a typical single pixel receiver system 6 years of continuous observing to complete. Prototypes of all major components have been completed and tested. The first 1x8 mixer row has been fabricated and has undergone testing. Fabrication, and assembly of the final waveguide components is now underway. SuperCam will be deployed with 32 pixels on the HHT in the Fall of 2008, with the remaining complement of 32 pixels to be installed at the end of the observing season.

Next generation heterodyne arrays with ~1000 pixels are possible with extensions and developments of today's technologies. With an additional level of integration to two dimensional focal planes, complexity is minimized. Such an instrument could be built for a reasonable cost on the timescale of new terahertz astronomy platforms such as the 10m SPT and the 25m CCAT telescopes.

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