SuperCam : A 64 pixel superheterodyne camera

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Abstract— We report on the development of *SuperCam*, a 64 pixel, superheterodyne camera designed for operation in the astrophysically important 870 µm atmospheric window. *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. The advent of such a system will provide an order of magnitude increase in mapping speed over what is now available and revolutionize how observational astronomy is performed in this important wavelength regime.

***SuperCam* is constructed by stacking eight, 1x8 rows of tunerless, SIS mixers. The SIS junctions use SOI (Silicon on Insulator) technology, with beamleads for device positioning and IF and ground electrical connections. The mixer modules are fabricated using a Kern MMP-2522 micromilling machine purchased specifically for this task. The IF output of each SIS device is directly connected to a low-noise, broadband MMIC amplifier module integrated into the mixer block. The instantaneous IF bandwidth of each pixel is 2 GHz, with a center frequency of 5 GHz. An IF processor constructed of eight 8-channel modules provides IF amplification, total power monitoring and baseband downconversion. A spectrum of the central 250 MHz or 500 MHz of each IF band is provided by the Omnisys real-time FFT spectrometer system, based on Xilinx Virtex 4 FPGAs. This spectrometer can operate in either 32 channel mode (500 MHz/channel) or 64 channel mode (250 MHz/channel). Local oscillator power is provided by a Virginia Diodes solid-state multiplier chain whose output is divided between the pixels with a matrix of waveguide power dividers. The mixer array is cooled to 4K by a closed-cycle cryostat with two cryocoolers. *SuperCam* will reside at the Cassegrain focus of the 10m Heinrich Hertz telescope (HHT) with a dedicated re-imaging optics system.**

All subsystems of *SuperCam* have completed the development stage, and are undergoing testing. We present test results for the *SuperCam* LNA modules, integration of LNAs in a test mixer, IF processor performance, spectrometer performance, cryogenic system verification, and end-to-end measurements of the IF chain and backend. Results from the fabrication, construction and testing of prototype SOI mixers, in both single pixel and 8 pixel versions will be shown. We will enter the final fabrication stage in early 2007, with expected completion in late 2007. Science operations are expected to begin in Spring, 2008.

***Index Terms*—Submillimeter heterodyne array**

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I. Introduction

SuperCam will operate in the astrophysically rich 870µm atmospheric window, where the HHT has the highest aperture efficiency of any submillimeter telescope in the world and excellent atmospheric transmission more than 40% of the time. The proposed Superheterodyne Camera (SuperCam) will be an 8x8, integrated receiver array fabricated using leading-edge mixer, local oscillator, low-noise amplifier, cryogenic, and digital signal processing technologies.

SuperCam will be several times larger than any existing spectroscopic imaging array at submillimeter wavelengths. The exceptional mapping speed that will result, combined with the efficiency and angular resolution achievable with the HHT, will make SuperCam the most uniquely-powerful instrument for probing the history of star formation in our Galaxy and the distant Universe. 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.

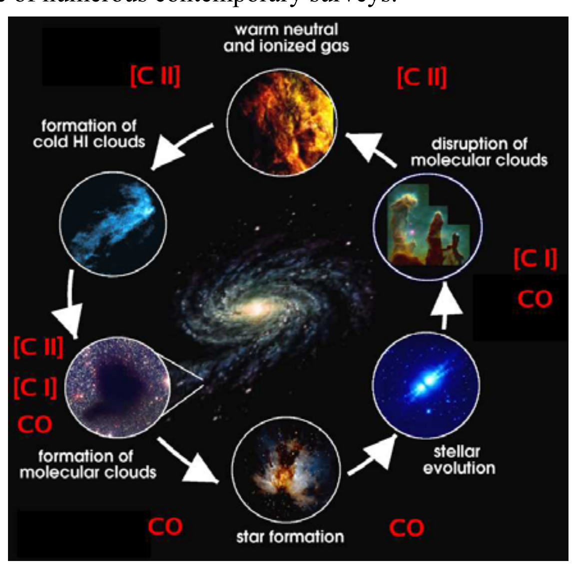

Figure 1: Life cycle of the ISM

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.

III. SuperCam Instrument Description

A. Instrument Design

Unlike all other millimeter/submillimeter arrays composed of individual mixers and discrete components, SuperCam has a high degree of integration. 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 8x8 integrated array of low-noise mixers. The array mixer contains first stage, low-noise, MMIC IF amplifier modules with integrated bias tees. A single solid-state source provides local oscillator power to each array mixer via a waveguide corporate power divider and a simple silicon etalon. Below we discuss SuperCam's key components.

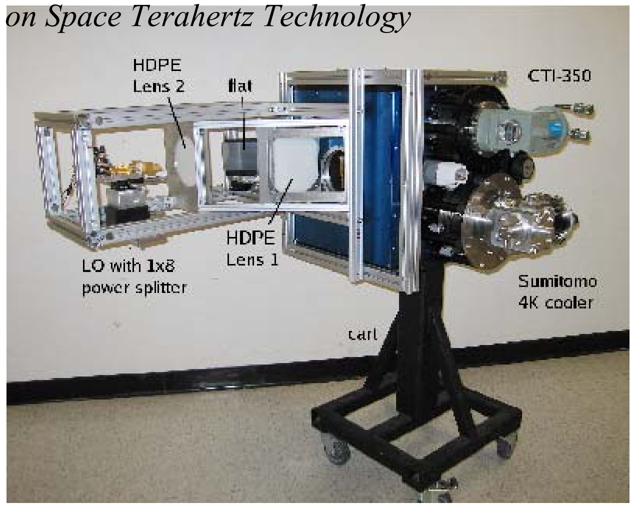

Figure 2: The SuperCam cryostat and optics

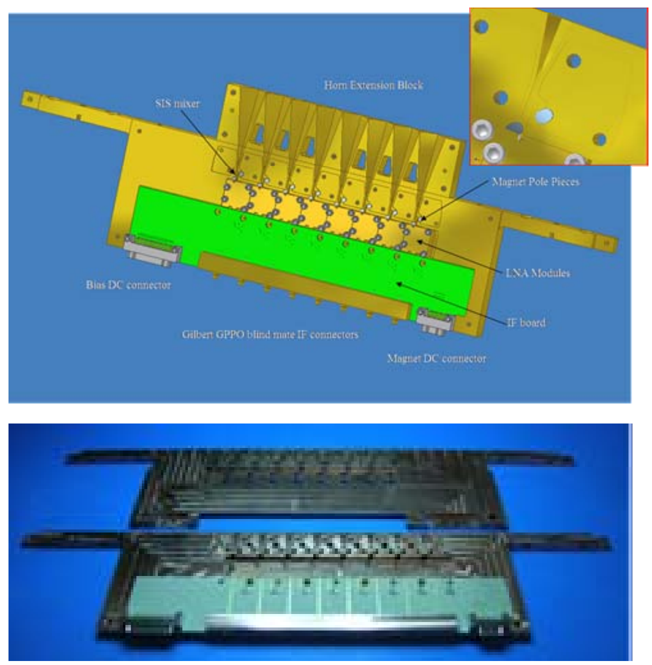

Figure 3: 3D CAD model of an open mixer array module (top) and a completed tellurium copper mixer block with IF board installed (bottom).

1) Cryogenics

The SuperCam cryostat with attached LO optics 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 127 mm diameter AR coated, crystalline quartz vacuum window and passes through an 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. Measurements using resistive heaters positioned in the cryostat at the location of the IF amplifiers verify that the cryogenic system has adequate performance, with an expected load capacity margin of ~50%.

2) Mixer Array

We are developing a compact, sensitive, 64 pixel array of SIS mixers optimized for operation in the 320-360 GHz atmospheric window. The two dimensional, 8x8 array will be composed of eight, 1x8 subarrays. 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 measured DSB noise temperature of this receiver (40 K) is excellent and essentially frequency independent across the band. The 1x8 mixer subarrays will be 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 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 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 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 tolerances.

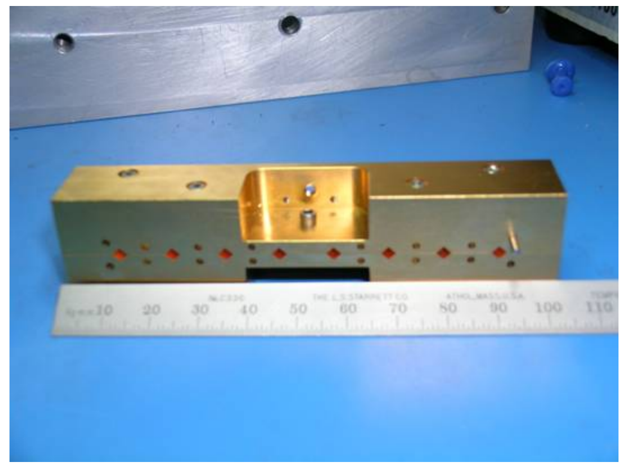

Figure 4: SuperCam 8-way LO power divider. The divider is based on a corporate array of E-plane y-splitters.

3) 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

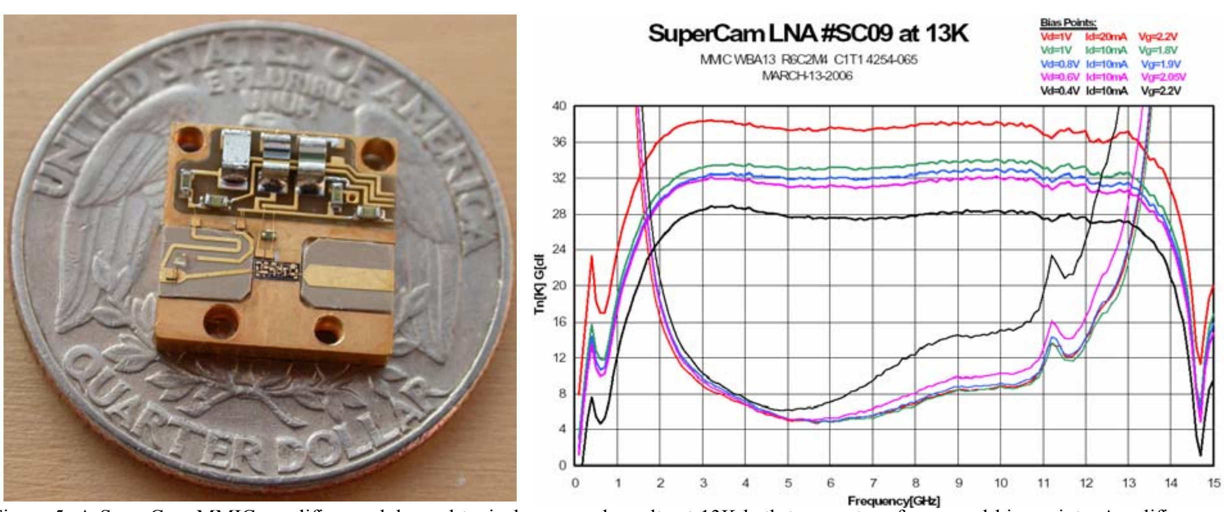

Figure 5: A SuperCam MMIC amplifier module, and typical measured results at 13K bath temperature for several bias points. Amplifier noise remains low for bias powers as low as 8 mW. Gain remains above 30 dB.

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 available 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 4 shows a prototype 1x8 power divider designed to power a single 1x8 mixer row. The final 64 way power divider will consist of 9 copies of this circuit, with a different block footprint. 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 silicon etalon diplexer is used to inject the LO power. This diplexer consists of a precisely polished silicon plate which acts as a fixed tuned Fabry-Perot etalon. This technique can couple 70% of the available LO power and over 99% of the sky power into the mixers, with no moving parts and simple optical alignment. As SuperCam is designed to spend extended periods of time tuned to a single frequency, this simple technique is preferred over more complicated tunable diplexers. A set of diplexers will allow tuning to any line of interest by switching silicon plates. 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.

Figure 6: SuperCam IF processor system for two SuperCam rows (16 channels).

4) *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 consuming 8 mW of power at 4K. The first 10 amplifier modules are complete., with all components necessary to complete all the modules finished. An example is shown in figure 5, with measured gain and noise data at 8 mW power dissipation. We have integrated an amplifier module into a single pixel SIS mixer and have verified that the amplifier module operates as expected. Allan varience times and mixer noise temperatures are unchanged within the measurement errors compared to a similar mixer used with an external commercial LNA and isolator. Similar tests have been performed with a single pixel mixer with beamlead devices, which will be described in section IV.

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. These modules have been extensively tested for stability and noise performance. Their stability is sufficient to avoid increasing the allen time of the array spectrometer, while adding less than 1K to the receiver noise temperature.

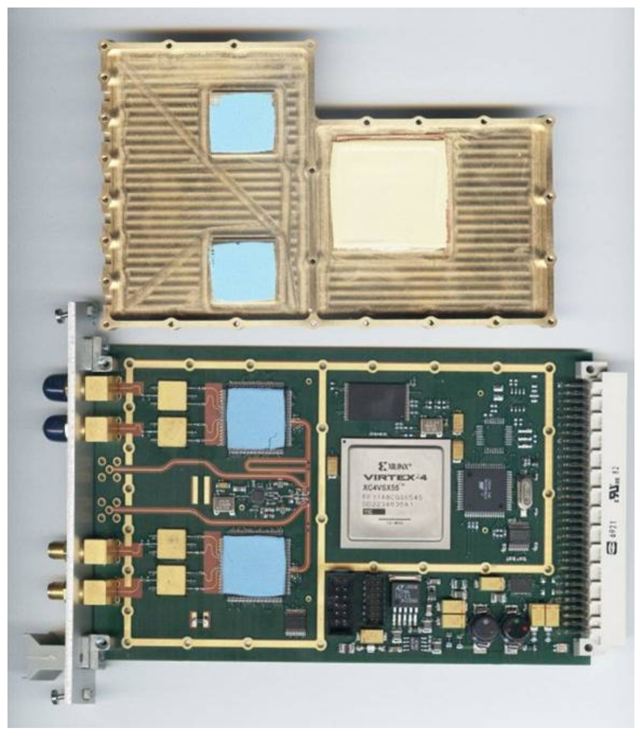

Figure 7: SuperCam FFT spectrometer board from Omnisys AB. This 3U board can process 4 500 MHz bandwidth IF signals or 2 1 GHz bandwidth IF signals at 250 kHz resolution.

5) *Array Spectrometer*

The SuperCam spectrometer will deliver 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 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 greater than 10 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 (shown in figure 7). This single 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 into the FPGAs. In addition, the spectrometer can be easily expanded to increase bandwidth. We have received 8 boards capable of processing 64x250 MHz, 32x 500 MHz or 16x1GHz IF signals. 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.

6) 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 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 a hyperbola and an ellipse with two flat mirrors. All the reimaging optics can be mounted on a single optical breadboard and left in the apex room. 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.

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 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 amplifier (shown in figure 8) that is an exact copy of a single pixel of the 1x8 mixer array design discussed in section III.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. The first batch of SIS junctions suffered from curling caused by a stressy oxide layer which made them difficult to mount, but successful testing was still possible. Lab results from the first device mounted are also shown in figure

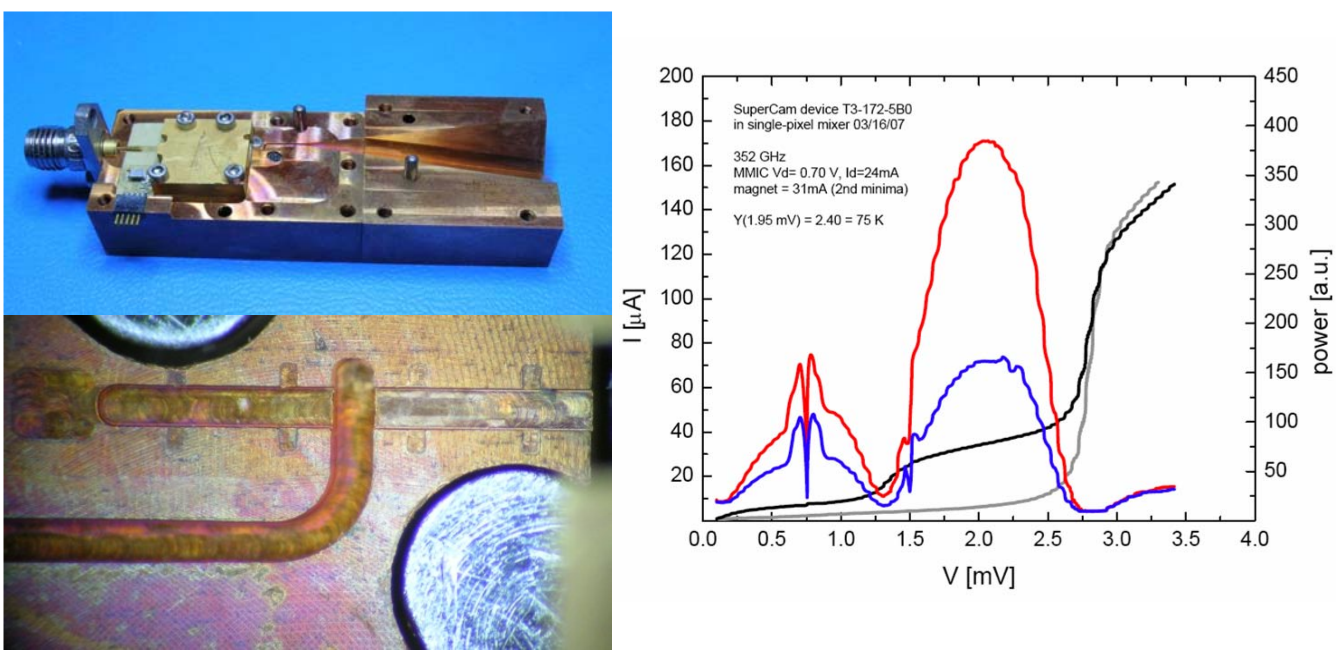

Figure 8: Single pixel test mixer with extended diagonal horn, LNA module and IF board (top left), a closeup of the device waveguide environment (bottom left), and a representative IV curve and hot/cold total power curve (right).

8. We achieved an uncorrected DSB noise temperature of 75K, and verified efficient operation of the electromagnet. Since these tests, a second batch of SIS devices has been delivered with the curling problem eliminated. This will facilitate rapid, self aligned mounting if the devices. With further optimization, we expect to be able to achieve the 60K receiver noise temperature predicted by the SIS device simulations.

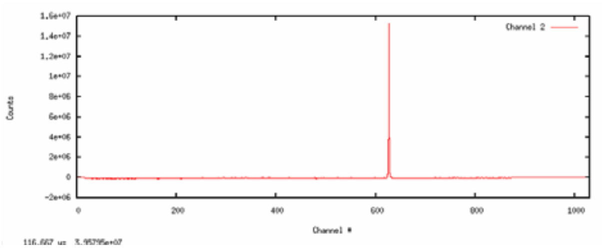

Figure 9: Spectrum from an end to end test of SuperCam prototype hardware.

In addition to measurement of these test mixers, we have also conducted an end to end test using prototype components of the complete SuperCam system. In this test, we used a line injector to detect a simulated spectral line using a single pixel test mixer with MMIC LNA module, a prototype IF processor module and an Omnisys FFT spectrometer board. The spectrum produced via this measurement is shown in figure 9.

V. 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 is now undergoing testing. We expect to complete fabrication and testing of the focal plane in 2007, with operations on the telescope to begin in 2008.

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