INTEGRATED HETERODYNE ARRAYS FOR FIR SPECTROSCOPY

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ABSTRACT

The advent of large format (~100 pixel) spectroscopic imaging cameras at submillimeter wavelengths would fundamentally change the way in which astronomy is performed in this important wavelength regime. While the possibility of such instruments has been discussed for more than two decades (Gillespie & Philips 1979), only recently have advances in mixer technology, device fabrication, micromachining, digital signal processing, and telescope design made the construction of such an instrument possible and economical. In our paper, we will present the design concept for a 10x10 heterodyne camera designed to operate at the prime focus of one of the 8.4 m mirrors of the Large Binocular Telescope, now under construction on Mt. Graham, Arizona. The array will be optimized for spectroscopic studies of galactic star formation regions in the 350 micron atmospheric window. Each pixel of the array will produce an 11" diffraction limited beam. The array field of view will be ~3.7 x 3.7 arc minutes. The unique optical and mechanical design of the LBT allows the instrument to be 'swung' into place in a matter of minutes. The instrument will be fully automated with all 100 spectra available on line after each integration. SuperCam could be ready for observations on the LBT as early as fall 2003.

The ability to obtain images and spectra simultaneously is key. In one day of operation, the proposed instrument will be capable of obtaining more high-resolution spectra than have *ever* been collected through the 350 micron atmospheric window. The array technology developed here is directly scalable to other frequency regions and has immediate applications in remote sensing of the Earth and its atmosphere, as well as space-based communications systems.

The 100 pixel superconducting/spectroscopic camera (SuperCam) will be designed to operate at the prime focus of one of the 8.4 m mirrors of the Large Binocular Telescope (LBT), currently under construction on Mt. Graham, Arizona. The array will be initially optimized for spectroscopic studies of Galactic star forming regions. Each pixel of the array will produce an 11 arc second diffraction limited beam. The array field of view will be ~3.7 x 3.7 arc minutes. The 'footprint' of the array on the star forming cloud M16

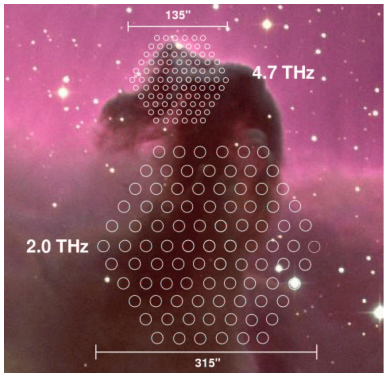

Figure 1: The array footprint of SuperCam at 4.7 THz and 2.0 THz overlayed on the Horsehead Nebula Each circle represents one diffractic limited beam (FWHM).

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is shown in Figure 1. The unique optical and mechanical design of the LBT allows the instrument to be ‘swung’ into place in a matter of minutes. SuperCam could be ready for observations on the LBT as early as fall, 2004.

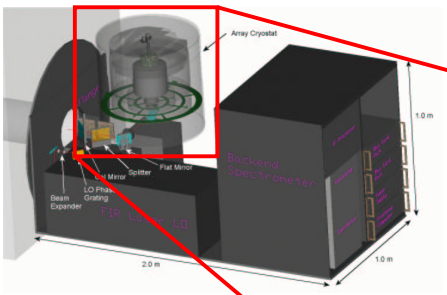

Figure 2: SuperCam mounted on the SOFIA telescope flange, with FIR laser LO, correlator and control electronics

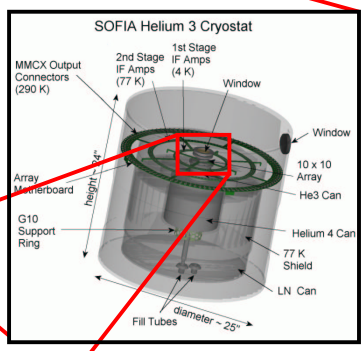

Figure 3: The SuperCam 3He cryostat, with "motherboard" based electronics providing cryogenic isolation.

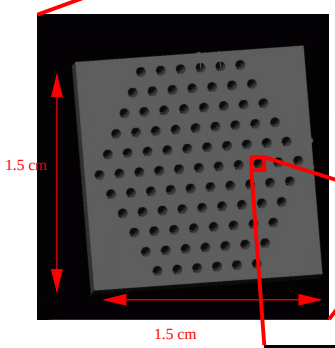

Figure 4: The 91 pixel array of dual mode feedhorns

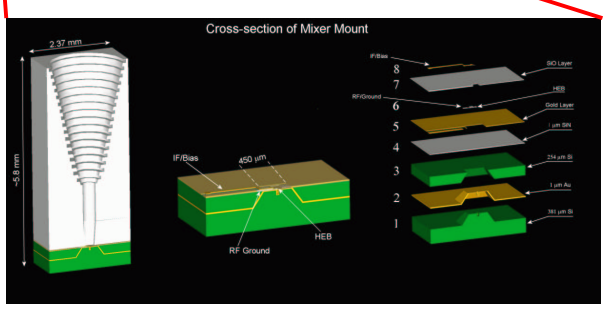

Figure 5: Cross section view of a single pixel. The array is composed of three main sections: the horn block, the bolometer wafer and the backshort block.

The future location of the array cryostat on the LBT is shown in Figure 2. A blow-up of the closed cycle cryostat used to cool the array is illustrated in Figure 3. At the heart of SuperCam is an array of waveguide mounted, Hot Electron Bolometer (HEB) mixers (Figure 4). The waveguide array will be fabricated with a custom, laser micro-machining system at the University of Arizona. Due to the small f/# at the LBT prime focus (f/1.142), the separation between individual mixers is ~1 mm. The entire mixer array will be 1.5 x 1.5 cm. Only the feedhorns themselves are needed to efficiently couple the mixers to the primary mirror. The array is wire bonded to the central ‘hub’ of three thermally-isolated, nested frames that form the array motherboard. The mixer array operates at a physical temperature between 1.5 and 4K. The inner frame is at 12K and contains the first stage of IF amplification (~10 dB) and the necessary bias circuitry. The second frame is at 60K and has an additional 30 dB of IF amplification. The third frame is at 300K and contains ~60 dB more IF amplification and is where the IF signals are connected to coaxial cable. Before this point, the IF signals are conveyed from one stage to another via microstrip lines.

The HEB is the ideal mixing device for an array application because the device is relatively easy to fabricate, and requires no magnetic field. SIS junctions offer good performance, but are very difficult to fabricate with the close to 100% yield we require. Since all devices are fabricated and mounted on a single nitride membrane, we cannot choose and individually mount the best devices. In addition, the 15mm x 15mm size of the

mixer array makes it impossible to provide a separate magnet for all 100 devices. A single, large magnet could be used, but the resulting magnetic field would not be optimum for all the devices. Compared to SIS junctions, HEBs are easy to fabricate, increasing the yield for a given run. In addition, they require no magnetic field. Currently, the performance of HEBs is competitive with SIS junctions at 810 GHz, and are the preferred device above 1 THz. New technologies, like the low Tc HEBs being developed at Yale, promise to outperform SIS junctions at 800 GHz and above (Siddiqi 2001). Figure 5 shows the Yale Nb-Au bilayer HEB device, both as a schematic and as a SEM image. Supercam could be constructed with more common Nb HEBs, or could be used with low Tc devices with the addition of a commercially available 3He stage to the JT refrigerator.

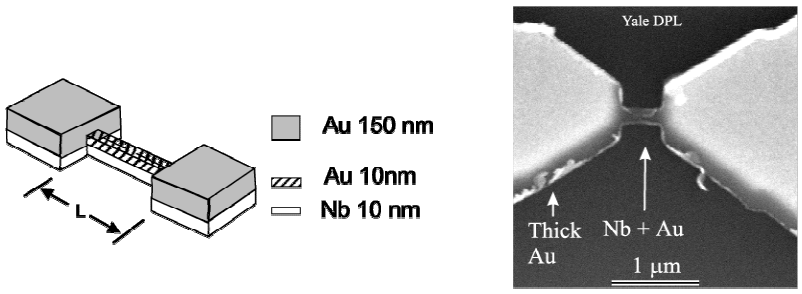

Figure 6: A schematic representation of the Yale bilayer low Tc HEB device a SEM image of a device fabricated using this concept.

Figure 6 is a detail of the mixer block itself. The mixer block is made of eight layers, in three subsections: the laser micromachined horn block, the bolometer block, with the devices fabricated on nitride membrane on a silicon frame, and a silicon backshort block. All the fabrication steps can be done with laser micromachining, wet etching, thin film deposition and e-beam evaporation. The structure is designed to be self-aligning to simplify assembly. The horn block consists of linear arrays of laser micromachined feedhorns, gold plated and bonded together in a 2-D array. The bonded array is then laser micromachined around the waveguide throats to create a Photonic Crystal Junction (PCJ) to prevent leakage of field into the substrate (Hesler 2001). The horns could be either corrugated dual mode horns, or smooth walled Potter horns. Potter horns are easier to fabricate, but have a 10% bandwidth as compared to the 30% of a corrugated horn. Since the 10% bandwidth of the Potter horn covers the entire 800 GHz atmospheric window, these would be suitable for SuperCam. The SuperCam mixer design does provide good performance from ~750-1100 GHz, so a corrugated horn would be necessary to cover the entire usable bandwidth of the mixer. Due to the very small f/D of the primary, a standard Potter horn or dual mode corrugated horn design has too directional a power pattern to yield a desirable edge taper. HFSS modeling has shown that lessening the flare angle of the horn while holding the other parameters constant broadens the beam without compromising the beam shape. With this modified horn design, it is possible to match the beam to the primary with a 10-15 dB edge taper. The bolometer block is fabricated from a silicon wafer with a silicon nitride membrane deposited on its top surface. The devices are fabricated on this robust wafer before etching. With the bolometer capped off, the wafer is then wet etched from the rear, creating a pyramidal pocket for each mixer, with a nitride window carrying the HEB. The nitride membrane provides the etch stop. The final component is a backshort block, fabricated from a silicon wafer. Pyramidal pillars that match the cavities created in the backshort block are wet etched using photolithographic techniques. The waveguide backshorts are then laser micromachined into the tops of the pyramidal pillars, along with PCJ crystals. Finally, the entire wafer is gold plated. A more detailed overview of the mixer design, with detailed full-wave electromagnetic simulations of mixer performance, can be found in these proceedings in a paper by J. Kooi.

Once the signal leaves the mixer block, the next challenge is to build an IF chain with suitable performance that is also cost effective. The motherboard design of SuperCam allows the use of small surface mount components. MMIC based LNAs are small, and have low power consumption and dissipation, lending them to a space-critical cryogenic design. Many groups are working to develop high performance MMIC amps that would be useful for SuperCam. In addition, it is possible to use inexpensive MMIC amps developed for communications applications. These amplifiers have limited bandwidth compared with custom made MMIC LNAs, but are extremely inexpensive. This type of MMIC is not designed to operate in a cryogenic environ-

ment, so testing is necessary to determine if the amp will survive thermal cycling, and will operate at a low temperature with suitable performance. An example is the Maxim 2640 LNA. This amp has survived multiple cryogenic cycles to 77K by being immersed directly into a LN2 bath, and allowed to warm in the ambient atmosphere with no protection against water condensation. In addition, we measured a noise temperature of 16K at a 77K physical temperature. Figure 7 shows the amp mounted on a test fixture that was used in the cryogenic tests. These tests lead us to believe that this amp could exhibit single digit noise temperatures at 12K or 4K. Gain was measured to be 12 dB at 77K. Since the amplifier is so small and inexpensive, multiple devices can be cascaded to generate the required gain. Further tests are necessary, but this amp is an example of may easily available communications components that could be used for the SuperCam IF chain.

The Local Oscillator (LO) will be either a new generation high power solid state LO or an existing far-infrared laser. The LO is injected by shining it directly into the cryostat window via the tertiary mirror of the LBT. Since no diplexer is needed, all the available LO power is available to the mixers. Also, the close spacing of the mixers in the focal plane relative to the horn aperture gives a focal plane filling factor of greater than 50%. This means that flood illumination of the focal plane is sufficient, negating the need for a phase grating or other beam forming system. To reduce cryogenic loading, the 4-wire bias network will be located on the 12K stage of the array motherboard, phantom feeding the bias to the mixers. Each mixer will be individually biased under computer control. The array's control electronics are based on a proven design used in many of Steward Observatory's single and multipixel receivers. The current design is based on 4 channel bias cards, with analog multiplexer cards feeding a PC data acquisition card. This system could be used for SuperCam in its current configuration, but new cards could easily be designed to take advantage of high density surface mount components, allowing 8-10 channels of bias per card.

The backend spectrometer for the array will consist of 100, 128 MHz wide, 2-bit correlator chips each with 128 lags. By restricting the correlator to a single chip per channel, platforming problems are avoided. In addition, the simplification of the RF section of the correlator creates a huge cost savings over a hybrid correlator design. The RF section of the correlator will be made to utilize the full IF bandwidth of SuperCam. The digital section will be designed for easy upgrades, so future, wide band correlator chips can be fitted when available. These correlator chips could offer up to 2.5 GHz of bandwidth and will be available in the near future. (Timoc 2002). Figure 8 shows a schematic diagram of the correlator design, which fits into a single 19" VME crate. The resulting velocity coverage (47 km/s) and resolution (0.87 km/s) is more than adequate for surveying most Galactic star forming regions. With upgraded correlator chips, extragalactic observations with bandwidths exceeding 900 km/s with 7 km/s resolution are possible.

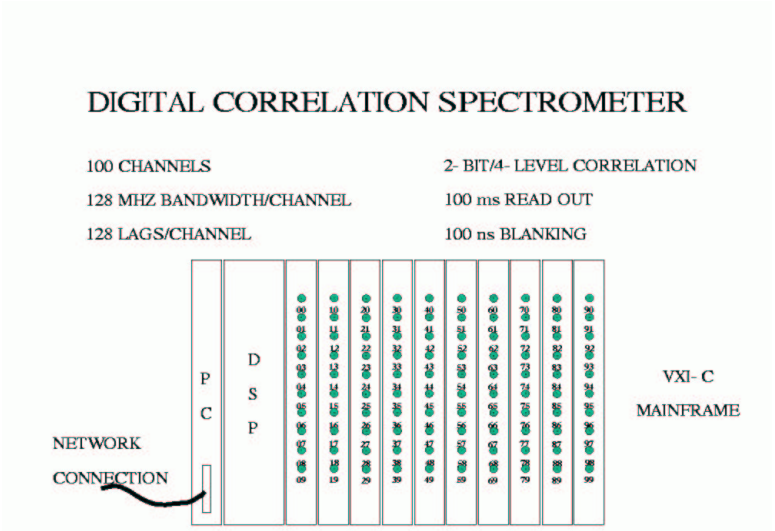

Figure 7: A schematic diagram of the Spaceborne Inc. 100 channel digital autocorrelator with relavent specifications for the first generation system.

Due to its size, design, and location, the LBT is an ideal instrument on which to test and optimize the performance of SuperCam. On the LBT, SuperCam will be operated primarily during twilight and daylight hours when the atmospheric opacity drops below 0.05 at 225 GHz. Within these constraints, Mt. Graham site statistics suggest the array will have ~100 hrs. of quality observing time from Nov.-Feb (Wilson 2002). Assuming a typical scan will be an hour in length, this translates into ~10,000 spectra per year. Once SuperCam has been used successfully on the LBT for at least two years, we plan to deploy it, or its clone, on the Nasmyth

focus of the 1.7 meter Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) located at the South Pole. From this site, SuperCam will be able to collect over 200,000 spectra per year (Stark 2001). Ultimately, SuperCAM will be used on the future South Pole 8 meter telescope, which will have an optical design very similar to the LBT (Stark 1998).

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