SUMMARY OF PERSONNEL AND WORK EFFORTS

PI Walker: The proposed effort will be a major component of the PI's research over the next three years. He will have overall responsibility for the project and coordinate activities between the various groups. He will spend ∼2 months per year working on the project. However, due to the PI's salary being maintained by his academic appointment, only graduate student support is being requested for this project.

Co-I Lichtenberger leads the team at the University of Virginia and will combine the HEB device expertise from the UMass group with their on processing expertise to make high quality arrays of HEBs. He requests 5% support per year for these efforts.

Co-I Yngvesson has a great deal of expertise in the area of phonon-cooled HEBs and will participate in the modeling, fabrication, and testing of devices. He requests 5% support per year for these efforts.

Co-I Kulesa brings experience with the bias electronics, control systems, and software used for submillimeter and THz frequency heterodyne arrays and has partaken in the integration of such an instrument (PoleSTAR) at the AST/RO telescope. He will participate in kind with the development of the proposed THz array. His salary is being provided by Steward Observatory.

Development of Integrated Array Building Blocks for Future Large Format Heterodyne Systems

1 Introduction

The advent of large format (∼100 pixel) spectroscopic imaging cameras in the far-infrared (FIR) will fundamentally change the way astronomy is performed in this important wavelength regime. While the possibility of such instruments has been discussed for more than two decades (Gillespie & Phillips, 1979), only recently have advances in mixer technology, device fabrication, micromachining, digital signal processing, and telescope design made the construction of such an instrument tractable. Here we propose to implement these technologies to develop the first integrated, far-infrared heterodyne array. The array will utilize NbN and NbTiN phonon-cooled Hot Electron Bolometers (HEB) in an efficient, micromachined, waveguide mount. HEB devices are inherently broadband, require very little local oscillator (LO) power and do not require a magnetic field for operation. These properties make HEBs ideal for array applications. The noise performance of HEBs starts to become competitive with SIS mixing devices at $\sim$ 1 THz and HEBs are the most sensitive mixer technology above 1.4 THz (Yngvesson 2003). It is in this frequency range where laser micromachining can be used to fabricate efficient, compact arrays of feedhorns and waveguide structures (Walker et al., 1998). The goal of the proposed effort is to demonstrate the viability of large format arrays in the FIR by developing a sensitive, single pixel 1.5 THz receiver that can serve as a building block for arrays and, once successfully tested, use this design to build a prototype 1x10 mixer array. Ultimately, the array would be used on the AST/RO telescope at the South Pole to perform [N II] observations of southern molecular clouds. Once such an array has been demonstrated, a technological roadmap to achieving the goal of large format, far-infrared (FIR) heterodyne arrays will become clear.

We have assembled a team with experience in each aspect of the proposed investigation. Co-I Yngvesson (UMass) is an expert in the field of phonon-cooled HEBs and will work closely with Co-I's Lichtenberger and Kooi in developing the optimum mixer design. Co-I Kooi (Caltech) will perform HFSS simulations of the mixers. Co-I Lichtenberger's team at UVa will be responsible for fabricating the HEBs from NbN and NbTiN films. The micromachined waveguide mounts, IF/bias electronics, cryogenics, optics, and IF processor will be the responsibility of the PI's group, including co-I Kulesa, at the University of Arizona. In addition, Karl Jacobs at the University of Cologne has agreed to provide high quality NbTiN films to the UVa team for patterning into HEBs. Members of this team have worked together in the past on a number of successful projects, including a 1.5 THz single pixel receiver (TREND) for AST/RO, a 4 pixel, 810 GHz array SIS receiver (PoleSTAR) for AST/RO, and a 7 pixel, 345 GHz array (DesertSTAR) for the Heinrich Hertz Telescope. In each case, this was the very first instrument of its kind. The experience gained in building these instruments will be fully utilized in the development of the proposed integrated array.

2 Scientific Motivation

2.1 High Resolution, Spectroscopic Imaging Arrays in the Far-Infrared

In the wavelength regime between 300 and 60 microns there are a number of atomic and molecular emission lines that are key diagnostic probes of the interstellar medium. These include transitions of [C II], [N II], [O I], HD, H_2D^+, OH, CO, and H_2O. In Giant Molecular Clouds (GMCs), evolved star envelopes, and planetary nebulae, these emission lines can be extended over many arc minutes and possess complicated line profiles that can only be disentangled using high resolution ($R = \lambda/\Delta\lambda > 10^6$) spectroscopy. Observations of these lines are crucial to understanding the delicate interplay between the interstellar medium and the stars that form from it. This feedback is central to all theories of galactic evolution, and it must be understood at high angular resolution in the Milky Way before it can be properly interpreted in external galaxies near and far. These spectral lines are pivotal probes of important physical processes because they relate directly to the chemistry and energy balance of the ISM; it is the cooling provided by these lines that partially regulates the collapse of molecular cloud cores into stars and traces the formation of molecules in evolved stars that ultimately replenish the ISM. Due to the hot (T $\geq$ 300K) and dense ($n_{\mathrm{H}} > 10^{10}\ \mathrm{cm}^{-3}$) conditions expected in many protoplanetary disks, emission lines in the FIR will also play a pivotal role in cooling and molding young planetary systems. Both high spectral resolution and imaging capabilities are necessary to probe velocity fields and disentangle the emission of protoplanetary disks from that of ubiquitous molecular outflows and ambient envelope and cloud material.

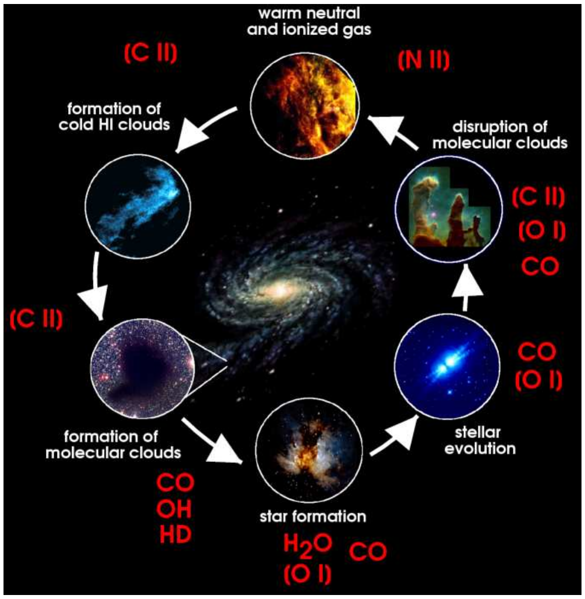

Figure 1: The life cycle of the interstellar medium and the stars that form from it; this relationship constitutes the basis for the evolution of galaxies, including our own Milky Way. Throughout this cycle, different (labeled) ionic and molecular species with strong emission lines at far-infrared wavelengths play pivotal roles in shaping the relevant physical processes.

The only instruments capable of realistically providing the required spectral resolution and spatial coverage for these studies are heterodyne array receivers. Unfortunately, none exist. Figure 2 compares the capabilities of SOFIA & Herschel's first light instruments in terms of number of pixels versus spectral resolution. When viewed in this way, there is a clear, urgent need for large format heterodyne instruments. Fortunately, recent breakthroughs in detector technology, micromachining, local oscillators, amplifier technology, and backend spectrometers now make the construction of large arrays of heterodyne receivers possible. The proposed 1x10 array for AST/RO will not only provide a technological roadmap for large format spectroscopic imaging cameras, it will also serve to demonstrate how such arrays can maximize the scientific return from single aperture telescopes such as AST/RO, the South Pole Submillimeter Telescope (SPST), SOFIA, and SAFIR. In terms of SARA program guidelines, the proposed work will 1) increase array format size, 2) reduce detector noise, 3) provide new fabrication and formatting techniques, and 4) extend wavelength coverage.

3 Technical Description

In the past the fabrication of integrated arrays of heterodyne mixers at submillimeter wavelength was prohibited by several factors:

- Sensitive mixing devices either did not exist or were difficult to fabricate.
- When mixers were available, their performance would often vary significantly from device to device.
- There was insufficient LO power to efficiently pump more than one or two detectors at any given time.
- Stacking more than a few mixer blocks together in the focal plane with their associated backshorts (if necessary), IF amps, magnets, bias lines, etc. was mechanically complex and could overload the cryogenic system.

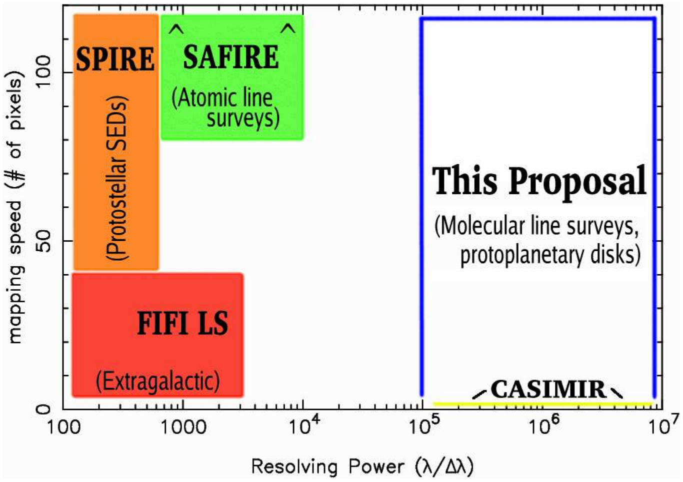

Figure 2: Overview of SOFIA/Herschel Terahertz-frequency spectroscopic instruments in development. The proposed instrument will provide a technological roadmap to making heterodyne arrays with 100+ pixels.

- The cost of the frontend components and the required backend spectrometer were prohibitive.

However, through the arduous efforts of many researchers in the field, most of these hurdles have now been overcome. In the following sections, we will describe plans for an instrument that combines a number of leading edge technologies to make a compact, sensitive submillimeter heterodyne array.

3.1 State-of-the-Art of Phonon-Cooled HEBs (PHEB) THz Heterodyne Receivers

Phonon-Cooled Hot Electron Bolometer (PHEB) heterodyne detectors for the frequency range 1 THz to 2.5 THz have recently developed into a well established technology for designing low-noise receiver systems for that frequency range. The first such receiver system on a radio telescope detected an astronomical spectral line from the Insterstellar Medium (CO, in 1998. Recently (October 2002 to February 2003), a team of researchers based at the University of Massachusetts, Amherst, with collaborators at UMass/Lowell, University of Arizona, the Harvard/Smithsonian Center for Astrophysics, and CalTech, installed TREND (Terahertz REceiver with NbN Device), an HEB receiver system for 1.25 THz to 1.5 THz at the AST/RO submillimeter wave telescope at the US South Pole Station. The TREND team included several of the investigators behind the present proposal. This receiver is ready to start observations now that periods of ultra-low precipitable water vapor weather will occur during the austral winter season UMass was one of the first groups to start developing the NbN HEB technology (1994), and thus has extensive experience in this field. NbN HEB devices in particular have a number of significant advantages:

1. A low receiver noise temperature over a wide tunable frequency range. Measured data with the twin-slot antenna are shown in Figure 3 [LEFT]. Similar bandwidth can be expected in the waveguide version. A waveguide mounted NbN HEB device was recently tested by Kawamura et al (2003) and yielded comparable receiver noise temperatures over a similar frequency range.
2. NbN PHEB devices are very insensitive to changes in applied LO power (= bias current) or bias voltage, as shown in Figure 3 [RIGHT].
3. The device size is not as small as that of diffusion-cooled devices. A typical optimum size is 0.4 ?m (length) x 4 ?m (width). The devices are thus relatively easy to fabricate with high yield. E-beam lithography is preferred.
4. The LO power required for a device of the size in 1) is of the order of a few hundred nW, which is sufficiently low to be supplied by either multiplier or laser sources.
5. The (THz) impedance is easily adjusted to the required value which matches an antenna or waveguide circuit. In particular, the 40 ohm impedance of the waveguide structure presented in this proposal can be met by a slight widening of the device.

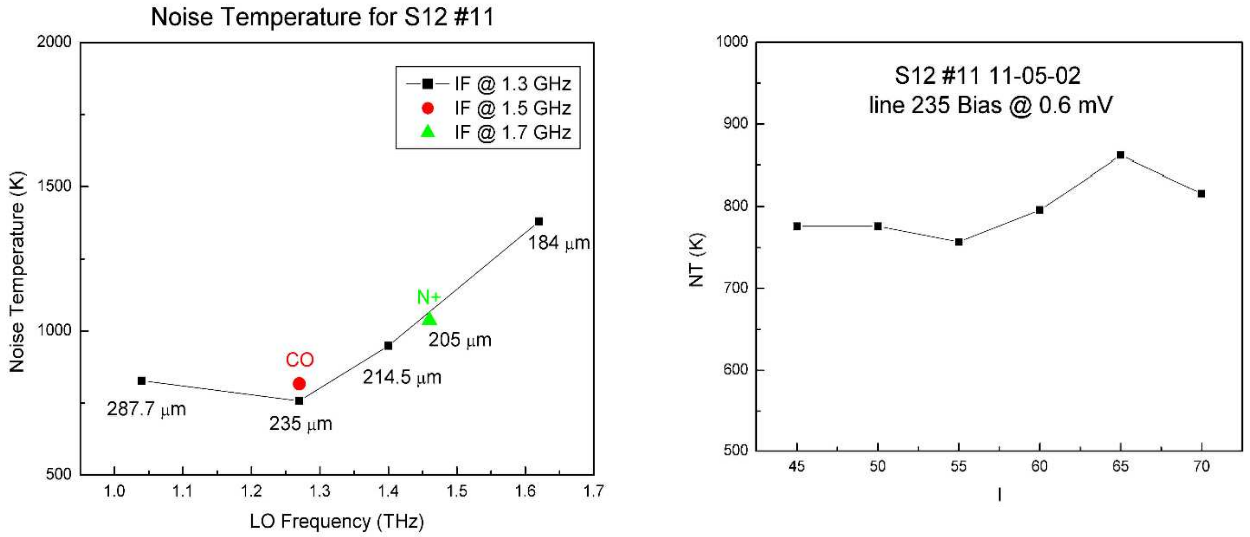

Figure 3: [LEFT]: Receiver noise performance of the HEB device for TREND. [RIGHT]: PHEB sensitivity to LO power and bias voltage.

6. The IF bandwidth at which the noise temperature has doubled compared with low IF frequencies (the "Receiver Noise Temperature Bandwidth") is about 5.5 to 6 GHz for device as has been shown by recent measurements at UMass.
7. NbN films are available from an experienced source (Moscow State Pedagogical University), and are under development at the Univ. of Virginia. NbTiN films are another, more recent alternative, which have shown roughly similar performance. UVa is also developing the capability to deposit these films. In the interim, Karl Jacobs at the University of Cologne (see commitment letter) has agreed to provide them.
8. The UMass group is developing a series of diagnostic and modeling techniques funded by a contract from NASA Langley Research Center, which can be used in the proposed effort.
9. Silicon is a preferred substrate, and is compatible with the technology proposed here. The silicon substrate need only be 1 to 2 μm thick to guarantee normal functioning of the HEB.
10. UMass/Amherst is using a flexible laser system and the group is experienced with testing of all aspects of HEB devices over a wide range of THz frequencies.

3.2 Beamlead HEBs in Waveguide Mounts

3.2.1 Necessity and Design Concept

Excellent progress in the development of Submillimeter-wave SIS and HEB mixers has been demonstrated in recent years. At frequencies below 800 GHz these mixers are typically implemented using waveguide techniques, while above 800 GHz quasi-optical (open structure) methods are often used. In many instances though, the use of waveguide components offers certain advantages over quasi-optical techniques as they are based on well-established microwave practices. Some examples include: Focal plane array receivers with feedhorns that produce well-defined on axis Gaussian beam patterns, balanced receivers that efficiently use all of the available LO power (no need for beam splitter or narrowband diplexer/etalon), the construction of sideband separation receivers, and the possibility of continuous comparison (correlation) receivers.

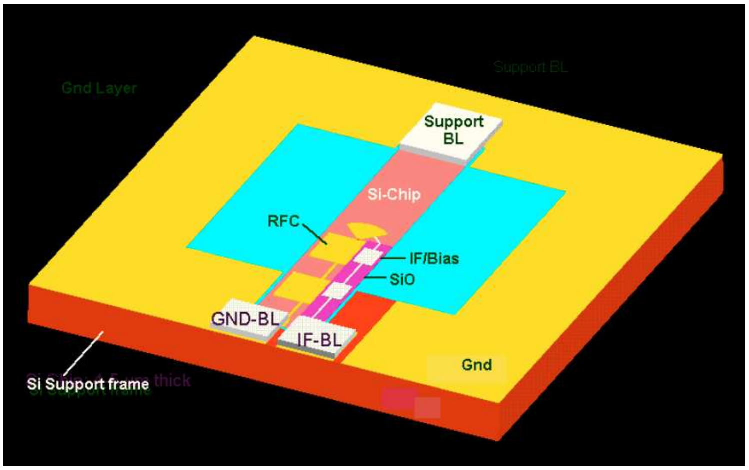

Figure 4: Rendering of the beamlead chip seated in a silicon carrier block. For the 1800 GHz center design, the chip width is 50μm and has a nominal thickness of 4-6 μm. The IF/Bias lines use part of the RF choke as a ground layer and are separated from the ground plane by a 0.2μm SiO insulating layer.

Over the years a number of waveguide to microstrip transitions have been proposed; most of which are implemented in reduced height waveguide with <35% RF bandwidth (Tong et al., 1996). Unfortunately reducing the waveguide height makes machining of mixer components at terahertz frequencies very difficult if not impossible. It also increases RF loss as the current density in the guide is increased. An additional disadvantage of existing high frequency waveguide mixers is the way the active device (SIS, HEB, Schottkey diode) is mounted in the waveguide. Traditionally the junction, and its supporting substrate, is positioned in a narrow channel across the waveguide. This structure forms a partially filled dielectric waveguide, whose dimensions must kept small to prevent energy from leaking out the channel. At frequencies exceeding a terahertz this mounting scheme becomes impractical. Because of the fabrication and mounting challenges, quasi-optical mixers are typically used at the shorter wavelength. However, published results from quasi-optical THz mixers have been all single pixel, and their designs are not necessarily scalable to the kind of imaging arrays we are proposing to build.

We believe that to move forward into the teraherz regime a much more integrated approach is required. To do so however one has to consider the requirements of the actual mixing device, in this case a phonon cooled hot electron bolometer (HEB). First of all, for the response time to be fast (IF) there has to be a thermal bath for the phonon's to escape into. This excludes the use of micron sized silicon-nitride membranes (Kooi et al., 2001). Secondly, HEB mixers exhibit extremely large instantaneous bandwidth. Though advantageous in many respects, one has to be careful to avoid saturating the device with incident thermal radiation. A waveguide structure naturally does this. Thirdly, HEB devices produced to date have not proven to be very uniform across a wafer. Thus basing an entire focal plane array on the uniformity of single wafer is risky. A better approach is to have a design of many densely packed HEB mixer chips that (after processing) can be RF pre-selected. The added advantage of such a design is that the chips can be used in any type of mixer configuration, e.g. array, balanced or sideband separating.

Fortunately, development in several key areas make it now practical to consider integrated imaging arrays for the teraherz regime. For one, laser micromachining techniques allow successful waveguide designs to be scaled to terahertz frequencies (Walker et al., 1998). Secondly, GaAs beamlead techniques in high frequency multipliers have been used with great success (Schlecht, et al., 2001; Chattopadhyay et al., 2002). There is no reason to believe the same the same won't hold for silicon as GaAs and silicon have very similar physical properties. Thirdly, a very broad bandwidth full-height waveguide to thin film microstrip transition has recently been reported on by Kooi et al. (2003). The combination of a 45% RF bandwidth and full-height waveguide turns out to be ideal for HEB THz mixer designs. Fourthly, extensive membrane experience (Kooi et al., 1998) has shown the importance to suspend the substrate. Fifthly, photonic crystals junctions (Hesler, 2001) can be used to suppress stray (or scatter) fields. And finally, progress in electromagnetic field simulation tools such as HFSS (Ansoft Corp., 2002) has given us an important tool in not only optimizing, but also analyzing the designs against misalignment in any special dimension. It should

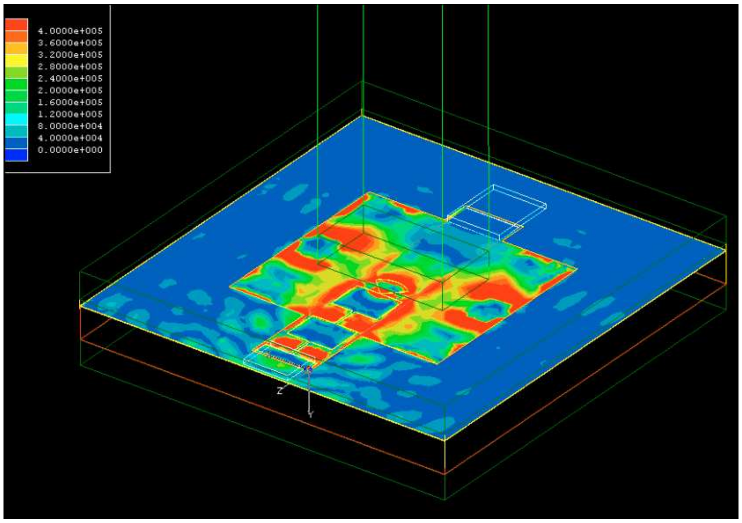

Figure 5: Electric Field distribution in the plane of the silicon beamlead chip. Note that even though there are strong fields in the space surrounding the chip, there is very little leakage, e.g. the coupling efficiency is better than 90% over the entire TE10 mode waveguide band.

be noted that the design is equally well applicable to SIS arrays for frequencies below a terahertz. In the latter case the magnetic field required to suppress the Josephson currents will have to be applied uniformly across the entire wafer (HEB mixers do not require a magnetic field, making them attractive mixing devices for larger scale spectroscopic imaging arrays).

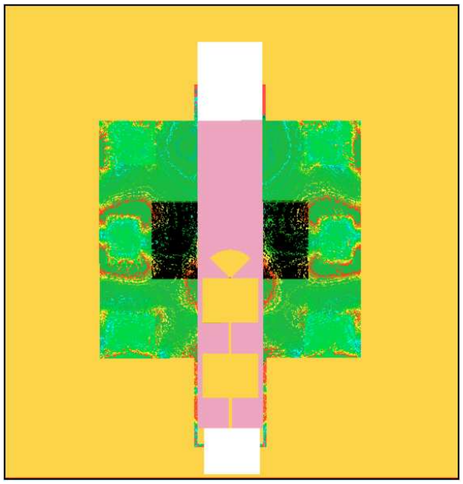

Figure 6: Top view of the silicon beamlead chip. Note how the photonic crystals (just 4 μm in height) help disperse the E-field leakage outside the waveguide. The beamlead chip is suspended in 6 μm of "air".

3.2.2 Model Results

The silicon chip (described in Section 3.3) vertical alignment is set by the beamleads. Extensive HFSS computer simulations show the chip height variation to be very tolerant (Figure 7), and in any event to be much larger that the specified "SOI" (Si "device-layer"/insulator "thin" /Si "handle") substrate variation of 0.5 μm. Sideways alignment of the beamlead chip is set lithographically, and is not an issue (small fraction of a wavelength). For the 1400–2200 GHz design, the silicon chip is suspended by 6 μm of space on both the top and bottom giving it an effective dielectric constant of 3.2. We anticipate using a combination of wet etching, reactive ion etching (RIE), and laser silicon micromachining techniques. All dimensions are well within the capabilities of these techniques. Test chips with less than 10 μm of clearance have been fabricated and yield no handling problems.

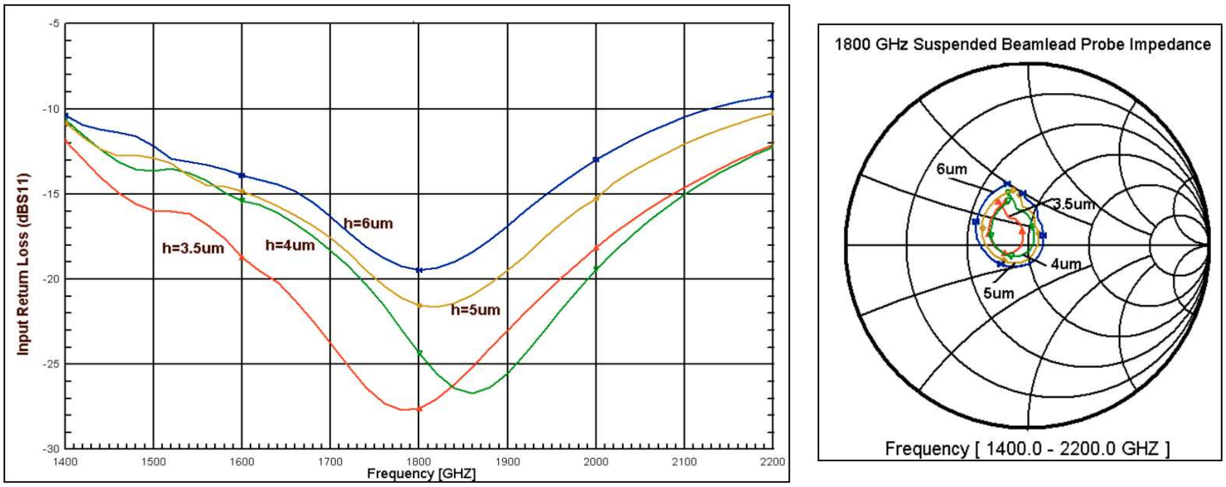

Figure 7: **[LEFT]:** Input return loss for the silicon beamlead chip as the substrate thickness is increased from 3.5 μm to 6 μm. In each case the backshort position was adjusted to optimize the results. It is evident that the silicon substrate height variation is very non-critical as long as the backshort depth is compensated accordingly. **[RIGHT]:** Beamlead chip input impedance. The impedance locus is centered around 40 Ω, which is determined by the structure. Varying the substrate height has little effect on the probe impedance, e.g. performance.

3.3 Beamlead Device Fabrication

At UVA we have developed a high yield, precise quartz beam lead process for SIS millimeter array applications (Bass et al., 2003a, 2002). We are currently working toward a Si based thin-chip beam lead process suitable for the micromachined HEB receiver applications discussed in this proposal. While our existing quartz based beam lead process uses a dicing saw and lapping to define the finished chip dimensions, the requirements of our proposed THz elements require much greater dimensional control than these techniques could afford.

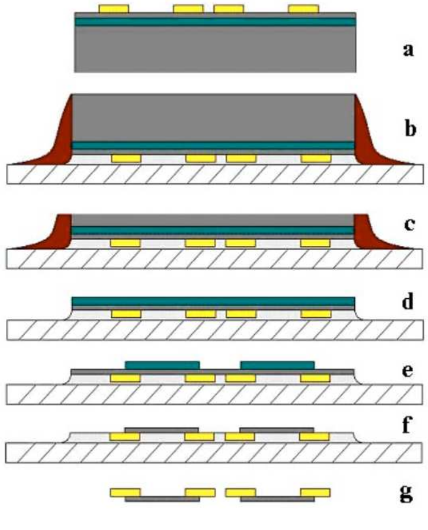

Figure 8: UVA SOI process for fabricating beam lead ultra thin Si mixers: (a) the beam leads and mixer circuitry are first fabricated atop an SOI wafer, (b) the SOI wafer is then mounted device side down on a glass carrier wafer and (c, d) the handle silicon removed, (e) the oxide layer is patterned and etched and (f) then used as a mask for an anisotropic Si reactive ion etch to precisely define the chip perimeter and then removed, and (g) the chips are complete following separation from the carrier wafer.

Our Si based approach begins by first fabricating the desired superconducting circuits atop the device layer of a "SOI" (Si'device-layer'/insulator'thin'/Si'handle') substrate. We have access to SOI wafers with Si device layer thickness between 0.5 and 10 μm with a tolerance of better than 0.5μm. The remaining beamlead process is shown in Figure 9. The beam leads are next fabricated using our established thick resist and plating process. The SOI chip is then mounted, device side down, atop a quartz carrier wafer using a clear mounting wax that has a melting point of ∼100C. Mounting the wafer with a transparent wax and carrier wafer allows for a subsequent backside lithographic alignment process to properly orient the wafer with respect to the circuit and beam lead structures for the subsequent precise chip perimeter lithographic and RIE steps. A combination of mechanical lapping and chemical etching is next used to remove the thick bulk "handle" silicon layer. The revealed oxide layer is next patterned using backside photolithographic alignment and RIE etching. The patterned oxide then serves as an etch mask for a reactive ion etch of the exposed device silicon. The device silicon is etched through to the quartz carrier and gold beam leads, thereby precisely defining the individual chips. The chips are then removed from the carrier wafer by dissolving the mounting wax.

To date we have developed an SOI wafer process (Bass et al., 2003b) that is compatible thermally and chemically with the processing of the HEBs and mixer circuitry on the SOI wafer. **Our initial efforts have demonstrated that we are able to fabricate chips with this process and handle Si chips with a single thickness (no frame) as thin as 1 micron as shown in Figure 9**. We have gone to pains to develop this process so that it will be compatible with our existing beam lead technology. Likewise, this process should also be compatible with our established HEB processes.

We propose to integrate this new SOI process with our existing beam-lead technology and our proven ability to fabricate HEB structures in order to fabricate ultra-thin chip beam-lead HEB mixer elements suitable for the proposed integrated focal plane arrays. We have previously demonstrated the ability to form high yield beam lead structures on quartz. We have also an established HEB fabrication process using a focused ion beam (FIB) tool to carve the HEB structure (Datesman & Lichtenberger, 1999; Datesman et al., 2001). We have recently also developed a more traditional Ebeam resist process for fabricating HEB structures (Bass et al., 2003c). It should be noted that these processes are suitable for defining both phonon cooled and diffusion cooled HEB geometries. Our UHV magnetron sputtering system is also equipped for sputtering Nb and NbTiN films for these devices.

With this SOI process we have excellent control of both final chip thickness and lateral dimensions to better than 0.5μm. Final chip thickness can also be measured in our laboratory to better than 100nm accuracy. Coupled with the capabilities of Arizona's laser based micromaching tool in forming the remaining waveguide blocks and 'accepting' fixturing for the beam lead arms, along with the use of UVA's FIB system for local trimming of the critical waveguide block features, we should be able to use this beam lead thin-chip technology with integrated receiver arrays to great advantage.

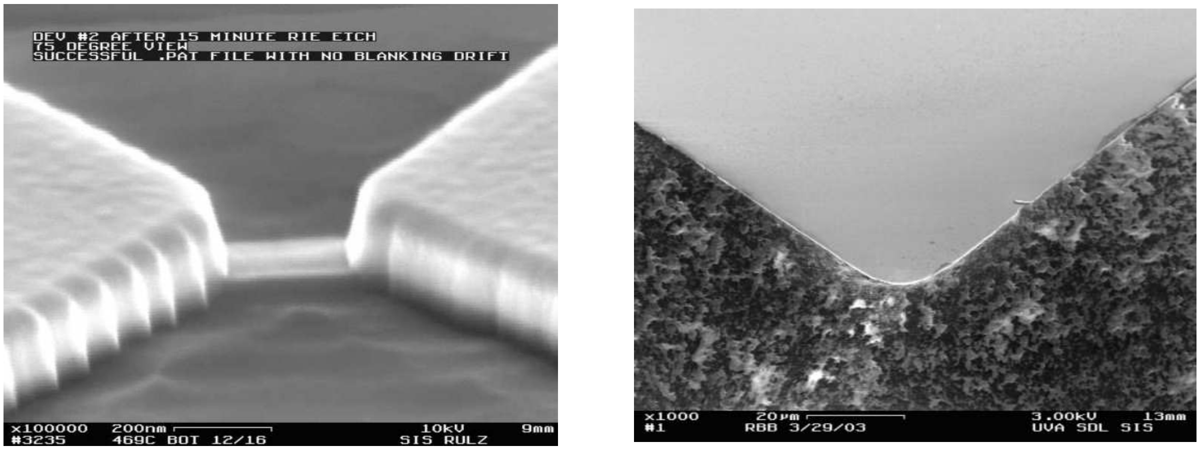

Figure 9: **[LEFT]:** SEM image of an HEB structure formed with our focused ion Beam (FIB) process. It should be noted that these processes are suitable for defining both phonon cooled and diffusion cooled HEB geometries. **[RIGHT]:** The chip is a prototype for future THz chip designs that will feature non-linear superconducting mixing elements, microwave circuitry, as well as thick gold beam leads. The gold beam leads will provide electrical and thermal contact for the chip. The beam leads will also serve as a mechanical support, allowing the chip to be suspended in the middle of a waveguide.

3.4 Micromachined Waveguide Mounts

HEBs have been successfully used in both quasi-optical and waveguide mixer mounts (Burke et al., 1999; Kawamura et al., 2001). When waveguide and quasi- optical mixers are made at the same frequency with comparable mixing devices, laboratory measurements show waveguide mixers outperform quasi-optical mixers both electrically and optically (Kooi et al., 1998, 1994; Walker et al., 1992). This occurs for two reasons: 1) because waveguide has an intrinsically lower loss than the microstrip structures used in planar designs, and 2) waveguide feedhorns can couple to the fundamental Gaussian mode with a 98% efficiency, compared to the $\leq$ 89% efficiency of dielectric lens-planar antennas (Goldsmith, 1998).

At wavelengths shorter than 400 μm (800 GHz), rectangular waveguide structures, feedhorns, and backshorts become extremely difficult to fabricate using standard machining techniques. We have used a new laser milling technique to fabricate high quality, THz waveguide components and feedhorns. Once metallized, the structures have the properties of standard waveguide components Walker et al. (1998). With this process, waveguide components of varying height and width can be machined quickly and at low cost to an accuracy of ~ 1 μm. *By combining this new laser micromachining process with HEBs, the construction of high performance, large format, waveguide imaging arrays at THz frequencies becomes possible*.

As a demonstration of the impact of laser micromachining technology, single proof-of-concept 1.5 THz corrugated feedhorns and 1x10 arrays of 1.5 THz corrugated horns were fabricated using the laser micromachining system at the University of Arizona. Figure 10 is an electron microscope image of a 1.5 THz corrugated feedhorn, with $\lambda/4$ waveguide matching to full-height rectangular waveguide. Figure 11 demonstrates the repeatability and consistency of the laser micromachining process. The entire array of feedhorns was etched in less than 2 hours.

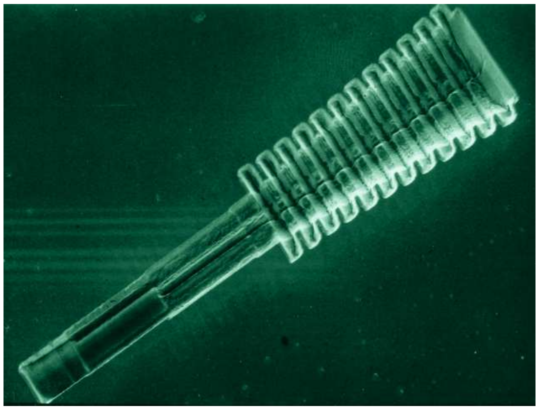

Figure 10: SEM of portion of a prototype 1.5 THz feedhorn and waveguide structure. The feedhorn and matching waveguide are together 2 mm long. The structure was etched using 4.3 Watts of laser power focused into a 6 μm spot in 200 Torr of chlorine gas. The laser beam was scanned at 5 cm/s and incrementally moved 2 μm between line scans. Under these conditions, nominally 1 μm shavings are removed per pass of the laser over the surface. The total etch time is one hour, not including the overhead time for pattern generation and stage motion.

As a test of our fabrication and assembly process, we performed beam pattern measurements on a laser micromachined 2 THz corrugated feedhorn (Walker et al., 1998). The differences between the theoretical and measured beam profiles were within the resolution limit and amplitude sensitivity of the test set-up.

Waveguide surface roughness values measured with atomic force microscopy are typically on the order of 200 nm RMS. This surface quality is already sufficient to provide low-loss waveguide performance to $\geq$ 10 THz. The RMS surface roughness can be reduced even further, to under 25 nm, using standard polishing etches based on HF-HNO_3-$HC_2H_3O_2$ solutions.

Our initial investigations into the application of laser micromachining were conducted under a Collaborative Research and Development Agreement (CRDA) between the PI (at the University of Arizona) and Lincoln Laboratory. One purpose of the CRDA is to transfer technology, such as the micromachining process described here, out of national laboratories into the private sector. Based upon the success of this collaboration, the Engineering Division of the National Science Foundation, NASA SARA program, and, most recently, Army Research Office have awarded funds to construct a laser micromachining system optimized for the fabrication of THz waveguide and optical components at Steward Observatory. This system is now fully operational and we are ready to use it for the development of imaging arrays.

3.5 *Focal Plane Array Concept*

All waveguide components for the arrays will be micromachined out of silicon and assembled into an integrated package. The array design and fabrication can be readily scaled for use at shorter wavelengths. To illustrate how 2D arrays can be fabricated with this technology, a conceptual design for a 4 × 4 array of micromachined fixed-backshort, waveguide mixers is shown in Figure 12. The focal plane array consists of a "Horn Block", "Bolometer Block", and "Backshort Block".

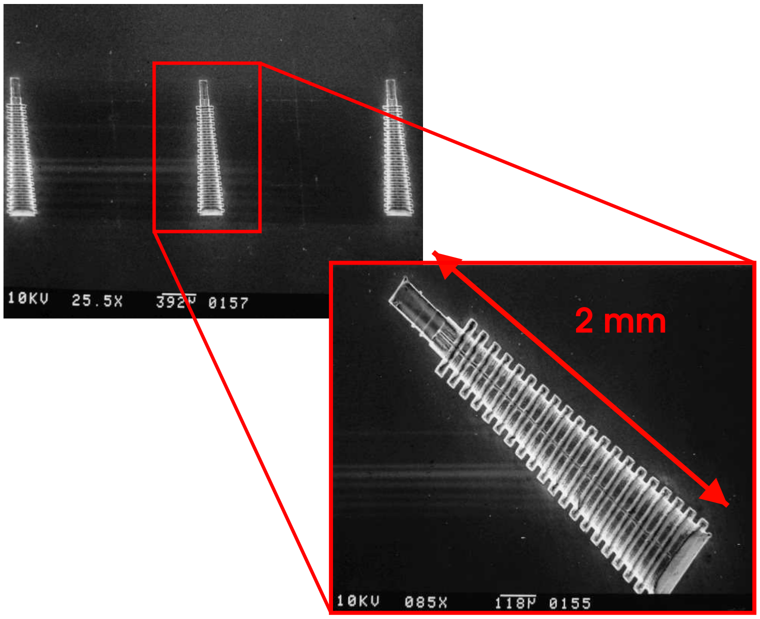

Figure 11: SEM of three laser-machined 1.5 Thz corrugated horns in a 1 × 10 array, demonstrating the accuracy and consistency of the Arizona micromachining system.

3.5.1 *Horn Block*

The Horn Block to be demonstrated in this proposal is assembled from a single 1 × 10 corrugated feedhorn subarray, formed by bonding two gold plated, silicon wafers in which mirror images of the corrugated feedhorns have been laser micromachined. Alignment between the two halves of a horn subarray is insured by posts and corresponding holes wet-etched in each half before laser machining. Assembly of the package will be done with the aid of an infrared microscope and micromanipulator system designed originally for flip-chip bonding. Each horn is micromachined with a circular-to-rectangular waveguide transition to match the input impedance of the HEB.

3.5.2 *Bolometer Block*

The Bolometer Block serves as the carrier for the beamlead devices and the 'PC board' on which DC bias is applied and IF power conveyed from the HEB. It too is made from silicon. The window and slots across which the HEB is mounted is formed using the laser micromachining system. If during assembly there is a small gap between the Bolometer, Horn, or Backshort Blocks, significant signal could be lost due to the generation of unwanted substrate modes. In the array design, we have reduced this effect dramatically by using a suspended stripline RF choke design similar to that of Blundell & Tong and micromachining a novel RF choke structure (Hesler, 2001) at the Horn and Junction Block interface. With these chokes in place, more than 1 mil (milli-inch) separation can be easily tolerated between the Horn, Bolometer, and Backshort Blocks. The choke and waveguide probe designs were optimized at both 1.5 and 5 THz by collaborator Kooi using Hewlett-Packard's High Frequency Structure Simulator (HFSS).

An exploded view of an individual mixer block is shown in Figure 13. The feedhorns and waveguide backshorts will be micromachined and gold plated by the Arizona group using existing facilities. The fabrication of the array Bolometer Block, including the HEB, waveguide probe, and IF output lines, will be a joint effort between the UofA and the UVa.

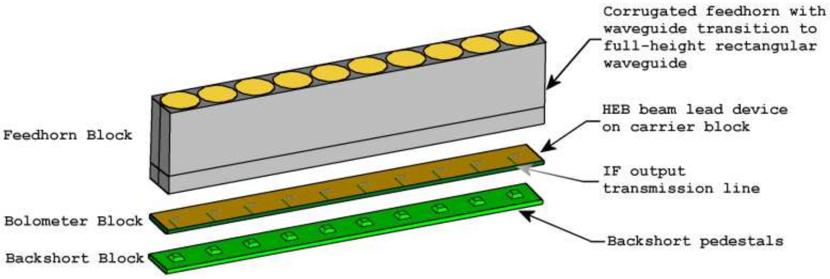

Figure 12: Assembly Drawing of a 1.5 THz Array Mixer Block

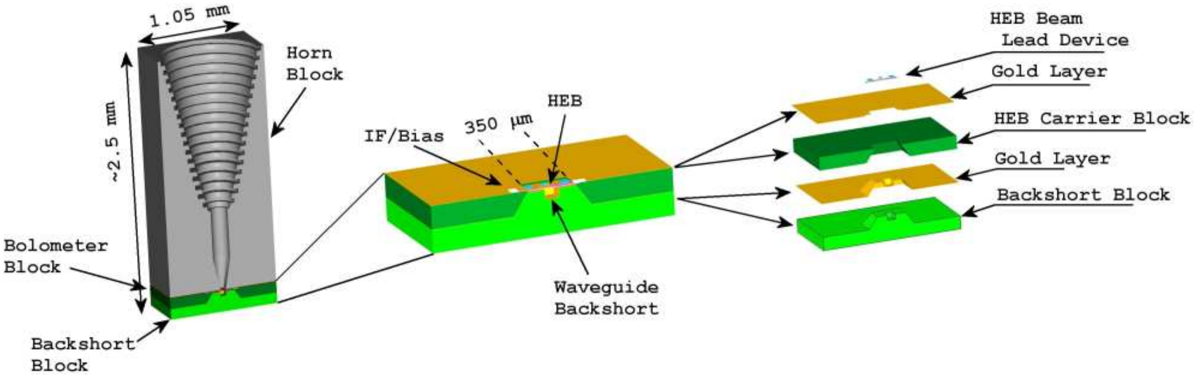

Figure 13: Exploded view of an individual array mixer assembly.

For heterodyne arrays efficient telescope illumination can be achieved with a $2f\lambda$ separation ($\sim 3\omega$) between feedhorns in the telescope focal plane. At the Nasmyth focus of AST/RO this separation is $\sim$ 3.6 mm. Since all the mixers share a common Bolometer Block, crosstalk between array pixels could be a concern. Using HFSS, we have carefully constructed a 2x2 simulation of an array with only ~1 mm separation and found the crosstalk to be down below the -35 dB level across the band. The separation between array elements in the proposed array is three times as great, suggesting crosstalk in the Bolometer Block will not be a significant problem.

The IF output of each mixer is ultimately conveyed to wire bonding pads on the periphery of the bolometer block by CPW lines. The IF impedance of HEBs provides a good, broadband match to 50 Ω transmission line, so no sophisticated IF impedance transformers are required.

3.5.3 Backshort Block

The fixed rectangular backshort is laser micromachined on a pyramidal structure designed to fit the cavity behind the membrane. The pyramidal structures can be readily made by wet-etching silicon through an SiN mask evaporated on the wafer (Rebeiz et al., 1987). Once etched, the Backshort Wafer is gold plated. With this design the performance of the array can be optimized in the lab by trying different backshort lengths.

3.6 IF/Bias Distribution system

3.6.1 IF Processing and Backend Spectrometers

Unlike the situation often encountered in conventional single pixel and array receivers, in the proposed system it is the choice of the IF frequency and bandwidth that determines the size and cost of the array camera. In the proposed design the waveguide mixers are micromachined out of silicon using computer controlled laser micromachining and wet etching techniques. With this approach it costs the same to make $\sim$4 mixers as to make just one. In both SIS and HEBs fabrication runs, typically 100's of devices are made at once on a single wafer. Since HEBs require $\sim$30 times less LO power than SIS devices, a commercially available FIR laser system can easily drive the entire array.

The additional cost per pixel is driven by the cost of the IF components and the spectrometer needed to process the signal. Fortunately these costs are also dropping. For the [N II], H_2D+, and CO 11-10 transitions, laser lines yielding IF frequencies of 1.7 GHz (Yngvesson, private communication), 7.64 (Borieko & Betz 1993), and 5.2 GHz (Chin 1980) are available. IF frequencies up to 7 GHz have been demonstrated to yield low noise response in NbN phonon-cooled HEBs (Yngvesson et al., 2002). Wideband, low-noise amplifiers are now available with sufficient bandwidth to cover all three IF frequencies (Weinreb 2003).

In an earlier effort, the PI and his collaborators designed and built a 4 pixel, 810 GHz array receiver. This system has a complete IF processing system, including a 4 x 1 GHz array AOS provided by the University of Cologne. We plan to utilize this system for field testing the proposed array. Funds for a 10 × 2 GHz correlator system to service the full array are being requested in a separate grant.

With the proposed approach, there is only a small cost increase in going from a single to multipixel system.

3.6.2 *Array Bias Control System*

A computer controlled array bias system has already been developed by the PI's group at Arizona and is currently being used with their 4-channel, SIS 810 GHz array (PoleSTAR) on the AST/RO telescope at the South Pole and a 7-channel, 345 GHz SIS array (Pleiades) soon to be installed on the HHT. The system allows manual tuning of each mixer and amplifier, plus automated bias point selection. All voltages (and currents) are controlled and monitored through a flexible graphical user interface (GUI) written in C and controlled by a single Linux-based PC. We will build a 10 channel version of this system for the proposed array.

3.7 *Local Oscillator*

The laser LO system for the array will be supplied by NASA/GSFC as a result of an SBIR development awarded to DeMaria ElectroOptics Systems (DEOS, now part of Coherent), of Bloomfield, CT, for the design and construction of a waveguide CO_2-pumped submillimeter local oscillator suitable for use on SOFIA (see supporting letter from G. Chen). The high output power of the SIFIR laser will provide ample LO power to pump HEB arrays of >100 pixels.

3.8 *Array Cryostat*

Before building the 1x10 array, we will conduct performance tests on single channel versions of phonon cooled NbN and NbTiN HEBs at UMass using a conventional wet dewar.

A new, larger cryostat will be needed for housing the 1x10 array. Our ultimate goal is to use the array on the Nasmyth focus of AST/RO (see Figure 14 below, and accompanying letter from A. Stark, AST/RO PI). For this we will need a closed-cycle cryostat capable of 4 K operation with very low microphonics. Commercially available (CryoMech Inc.) are now available that meet these requirements. These referigerators have mounting rings similar to that of a standard CTI 350 coldhead. For this project, We will modify an existing Precision Cryogenics dewar to accomodate the pulse tube referigerator. The load capacity of the pulse tube at 4K is *more than adequate* to cool both the mixers and the first stage IF amplifiers.

3.9 *Optics*

The array will be bolted on the Nasmyth focus of AST/RO as shown in Figure 14. This position was chosen because of the greater field of view it provides. From the warm receiver room (located just below the telescope) optical constraints limit the size of the array to 3x3. Although the proposed 1x10 array has only

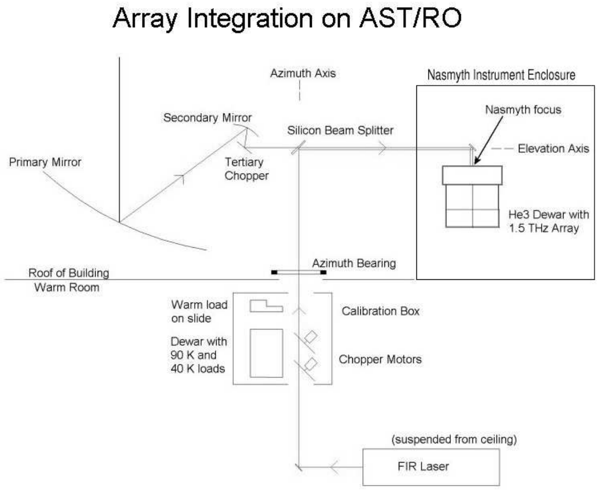

Figure 14: AST/RO optical path to the proposed hetrodyne receiver array at the Nasmyth focus

one more pixel, it has the advantage of being extensible to 100 or more elements. The instrument will be completely enclosed in a housing that will keep it at a suitable operating temperature.

The telescope beam first reflects off a secondary and tertiary mirror before it passes through a silicon beam splitter (Walker et al., 2001). The beam splitter injects the local oscillator beam from the FIR laser (located in the warm receiver room) into the focal plane array. The horns are already spaced to provide adequate coverage of the focal plane. Only a dielectric lens is required to make the final match between the telescope beams and the array feedhorns.

4 Educational Impact of Proposed Research

4.1 *University of Arizona*

Almost all the instrumentation designed and fabricated in the Steward Observatory Radio Astronomy Lab (SORAL) was done by students under the supervision of the PI. Past Ph.D. grads from the lab include Jason Glenn (now a faculty member at U.C. Boulder) and Gopal Narayanan (faculty member at U. Mass.). Currently, there are 4 grad students and 2 undergrads working in the lab on a wide range of instrumentation projects. When appropriate, the students use the instruments they have built toward their undergraduate or graduate degrees. Even though the salary of only one Arizona graduate student is requested, all the students will benefit from the project.

The PI is now in the process of organizing an ‘Astro-Technology’ initiative at the University of Arizona. The goal is to build a cross-disciplinary program that facilitates the exchange of faculty members, postdocs, students, ideas, and physical resources between departments (e.g. Astronomy, Planetary Sciences, Optical Sciences, and Electrical Engineering) interested in applying leading-edge technology to the solution of astrophysical problems. The proposed instrument will serve as a model for this initiative, illustrating how diverse technologies can be fused to provide a new, powerful instrument for observational astronomy.

4.2 *University of Massachusetts*

The subcontract to the University of Massachusetts will contain funds to support a graduate student to work with Prof. Yngvesson in designing and characterizing prototype HEB beamlead mixers. The student will work closely with fellow graduate students both at the University of Arizona and Virginia. It is likely that this student will also participate in field testing the array on AST/RO.

4.3 University of Virginia

The subcontract to the University of Virginia will be used to partly fund a graduate research assistant. The student will work with Dr. Lichtenberger and other team members to develop the optimum strategy for fabricating and assembling the micromachined components into a working mixer.

5 Plan of Action

	Arizona	**UMass**	**UVa**	**Caltech**
YEAR 1: Optimize Single Pixel				
• Complete single-pixel mixer models in HFSS				**X**
• Fabrication of first beamlead HEBs			**X**	
• Test single pixel performance		**X**		
• Laser-micromachine mixer blocks	**X**			
YEAR 2: Array Implementation				
• Complete array mixer models in HFSS				**X**
• Optimization of HEB beamlead devices			**X**	
• Build array cryostat	**X**			
• Help test performance of array at AZ	**X**	**X**		
YEAR 3: Field Testing at AST/RO				
• Fabrication of spare HEB devices			**X**	
• Build optics and mount for AST/RO	**X**			
• Install array at AST/RO	**X**	**X**		**X**

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FACILITIES, EQUIPMENT & OTHER RESOURCES

University of Arizona, Steward Observatory

In 1992 the PI established a laboratory (the Steward Observatory Radio Astronomy Laboratory, SORAL) for the development of state-of-the-art submillimeter-wave receiver systems. The laboratory contains (or has ready access to) all the equipment (spectrum analyzers, network analyzers, vacuum pumps, cryogenic support facilities, etc.) needed for the development of receivers.

The NSF Division of Astronomical Sciences awarded the PI funds to construct a 7 element array receiver at 345 GHz. This array will begin full operation on the HHT in October 2003. In the past, SORAL has produced facility 230 and 492 GHz receivers for the HHT and, recently, was the lead group in the design and construction of a dual channel 492/810 GHz receiver and 4 pixel 810 GHz array receiver (PoleSTAR) for AST/RO at the South Pole. The 492/810 GHz receiver has been in operation for 5 years and is the primary facility receiver for the telescope. The 810 GHz array was commissioned in November 2000 and is the first array to go into operation in this important atmospheric window. In Fall 2002, SORAL worked very closely with Sigfrid Yngvesson at UMass in preparing a single pixel, 1.5 THz HEB receiver for integration onto AST/RO. This instrument, TREND, is now in operation. The experience SORAL personnel have gained in the design and deployment of these receiver systems will be fully utilized in the construction of the proposed prototype systems.

As a result of its successful collaboration with Lincoln Laboratory in applying laser micromachining technology to the fabrication of THz components, the Physical Foundations of Enabling Technologies Program in the Engineering Division of the NSF awarded the PI a grant to construct a laser micromachining facility at Steward Observatory. This system is now fully operational. The design of this facility is based on the successful Lincoln Laboratory system and optimized for fabricating the mixer arrays described in this proposal. The availability of a state-of-the-art laser micromachining system at Steward Observatory provides the community with a *powerful, new* ability to develop a wide variety of needed THz components. Photolithographic facilities are also available at Steward Observatory and the Electrical Engineering Department for fabricating the wet-etched portions of the focal plane arrays.

Through a grant through the Defense University Research Instrumentation Program (DURIP), SORAL has recently purchased a new laser for the micromachining system, an e-beam evaporator for metallizing micromachined components, and a thin film deposition system for depositing nitride and other films.

SORAL also has licenses for both Ansoft's High Frequency Structure Simulator (HFSS) and Agilent Advanced Design Systems (ADS) software packages. These programs are used to accurately model and optimize mixers and other crucial receiver components.

University of Virginia

The Superconductor Device Laboratory (SDL) operates within the Applied Electrophysics Laboratory (AEpL) in the Department of Electrical Engineering at the University of Virginia. The primary facility consists of a 6,000 square foot laboratory, of which roughly two-thirds is clean room space. This facility is indicative of the institutional support that the SDL enjoys as a result of our long term commitment to excellent research in solid state technology, and also to education. The AEpL program involves graduate and undergraduate students, approximately thirty-five of which are currently involved in ongoing research.

The laboratory is fully equipped for the investigation and fabrication of complex Nb superconductive circuits. These processing capabilities include: UHV loadlocked 3″ DC magnetron sputtering of aluminum, niobium and gold in a dedicated trilayer system, high vacuum loadlocked 3″ magnetron sputtering of insulators and metals, UV and deep UV contact photolithography with sub-micron resolution, a Karl Zeiss 982 field emission scanning electron microscope with 1 nm resolution, two fluorine and a chlorine based reactive ion etchers, plasma etching, a multisource Temescal E-beam vacuum evaporation, dedicated ion milling station, and electrochemical plating and etching. The laboratory also has two high speed dicing saws, a computer controlled Tencor surface profiler, an FSM laser based thin film stress measurement system, and a Westbond wirebonder.

The SDL also benefits greatly from cooperative research efforts with other departments. In particular the Materials Science and Electrical Engineering Departments share an FEI-200 focused ion beam system ($500K). Also, a cooperative research program with the Department of Physics has led to the establishment of our Far Infrared Receiver Laboratory. This facility is fully equipped to design, assemble and evaluate millimeter and submillimeter wavelength mixers and multipliers. Sources include two submillimeter wavelength gas laser systems (300 GHz - 4.5 THz) and a variety of millimeter wavelength sources, multipliers and amplifiers from Millitech, J.E. Carlstrom and Radiometer Physics GmbH. A Bruker IFS 66V Fourier Transform Infrared Spectrometer (120 GHz - 225 THz) is available for materials and component evaluation, as well as HP network analyzers to 100 GHz (8510 and 8720s), spectrum analyzers to 110 GHz, and a variety of power meters, microscopes and probe stations. Computer systems include two HP 735 Apollo Workstations each running Hewlett-Packard's high frequency structure simulator and microwave design software.

University of Massachusetts

The Microwave and Electronics Laboratory (MEL) within the Department of Electrical and Computer Engineering at the University of Massachusetts, has an internationally recognized research and teaching program in the area of microwave engineering, and solid state devices. Most of the proposed effort will be performed within LAMMDA (Laboratory for Millimeter Wave Devices and Applications). A brief description of available resources, relevant to this proposal, follows. Microwave equipment, including several HP 8510 automatic network analyzers, one of which is usable to 60 GHz, is routinely used by graduate students, as well as a Cascade wafer probe, with probes to 40 GHz. We also have sources, and waveguide equipment, for frequencies up to 110 GHz. Microwave integrated circuits can be quickly fabricated in-house.. Measurements at low temperatures can be performed either in LN2 or LHe dewars, or in a CTI Model 350 mechanical refrigerator. One LHe dewar incorporates a superconducting magnet for fields to 5 T. Micro-fabrication facilities include a submicron mask aligner (Karl Suss MJB3UV), a multi-target sputtering system (Sputtered Film, Inc., S-Gun Turbosystem, Series II), and E-beam evaporator (CHA Industries, SE-600), a plasma reactive ion etcher (Microscience, Inc.), and a scanning electron microscope (AMRAY 1810D). A CO2 laser-pumped sub-mm gas-laser is available, with associated instrumentation, such as Spectrometer, power meters, detectors, interferometers, etc. A Fourier-Transform Spectrometer can be used for measurements from the Near IR to THz.