The Kilopixel Array Pathfinder Project (KAPPa): A 16 pixel 660 GHz pathfinder instrument with an integrated heterodyne focal plane detector

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Abstract*—KAPPa (the Kilopixel Array Pathfinder Project) is an effort to develop key technologies to enable the construction of coherent heterodyne focal plane arrays in the terahertz frequency regime with ~1000 pixels. The current state-of-the-art pixel count for coherent terahertz focal plane arrays is ~100 pixels (the Supercam 350 GHz array with 64 pixels). The leap to ~1000 pixels requires several key technological problems to be tackled before the construction of such a focal plane is possible. While the previous generation of arrays used 1D integration of mixer elements into a linear array module, kilopixel instruments will require 2D integration, as has been done with incoherent terahertz and infrared detectors. Over the next three years, the KAPPa project will develop a small (16-pixel) 2D integrated heterodyne focal plane array for the 660 GHz atmospheric window as a technological pathfinder towards future kilopixel heterodyne focal plane arrays in the terahertz frequency regime. KAPPa will use SIS devices fabricated on SOI membranes with beam lead alignment and connection features, designed for high yield and fast installation. A SiGe low noise amplifier with on-chip bias tee will be integrated directly into the mixer block immediately adjacent to each mixer. This amplifier has been designed to yield adequate gain and low noise temperature, while dissipating less than 2mW of power. The SIS and LNA devices will be mounted in a 2D integrated metal micromachined mixer array consisting of a backshort block containing the SIS device and LNA, and a horn block using drilled smooth-wall feedhorns. Magnetic field will be delivered to the devices via compact, permanent magnets embedded in the horn block. We will also develop cryogenically compatible IF flex circuits to replace individual semi-rigid coaxial lines for IF signal transmission. Once completed, this instrument will demonstrate the critical technologies necessary to construct coherent arrays approaching 1000 pixels for large single-dish THz telescopes like CCAT and SPT.

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I. Introduction

THE THz spectral regime is one of the last frontiers in both remote sensing and detector development. At this confluence of infrared and radio techniques, two approaches are used to detect THz radiation. Direct detection techniques, similar to those used in the infrared, have been pushed to lower energies to detect THz photons. Photoconductors have been built for astrophysics applications that operate at wavelengths up to ~200 microns (e.g. Herschel PACS [1], Spitzer MIPS [2]). For longer wavelength (THz) detection, cryogenic bolometer arrays have been developing at a rapid rate during the last decade. The UK SCUBA2 instrument, with 10,240 pixels at two THz colors (850 microns and 450 microns) is now being commissioned at the 15m James Clerk Maxwell Telescope [3]. This instrument will likely revolutionize astrophysics in the same way its predecessor SCUBA (with 37 pixels at 850 microns and 91 pixels at 450 microns) did a decade ago.

While direct-detection THz focal plane arrays are extremely valuable and have opened a new window on astrophysics, they do have fundamental limitations. Direct detectors do not preserve the relative phase information of arriving photons; therefore they deliver modest spectral resolution. Filters typically define ~10% imaging bandwidths. Fabry-Perot and grating spectrometers can be constructed and placed in front of the incoherent arrays to disperse the incoming light, but offer modest spectral resolution (R<1000-10,000) and cannot simultaneously spatially and spectrally multiplex. They are therefore primarily used to image thermal emission from dust in astronomical sources. For astronomical and atmospheric applications, there is considerable interest in the behavior of gas species. To disentangle their motions, instruments with high spectral resolutions are required (R>10,000). In

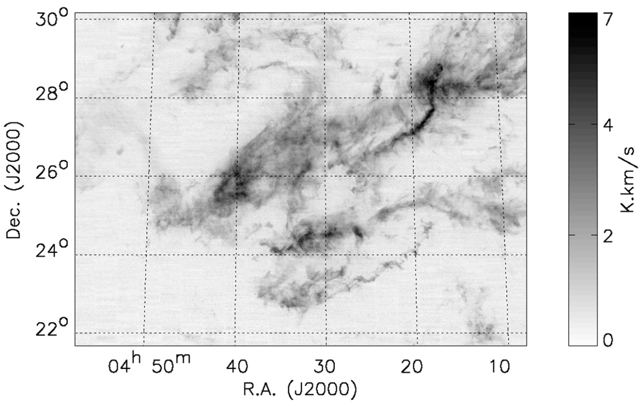

Fig. 1. An integrated intensity image of the Taurus molecular cloud complex covering over 120 square degrees on the sky in the light of the ^{13}CO(1-0) transition made with the SEQUOIA 32 pixel coherent array [4], [5].

molecular clouds, this gas makes up ~99% of the material by mass, and is the dominant player in the physics of star and planet formation. Kinematic information extracted from spectra collected using coherent techniques allows the detailed study of gas dynamics, in addition to the chemical information collected from the detection of a particular gas species. Various gas species have emission lines in the terahertz waveband that offer a huge wealth of information. They can be used to determine gas properties of the interstellar medium (ISM), such as mass, kinematics, temperature, density, and chemical composition. Large scale surveys of these lines both in the Milky Way and beyond can be used to help answer long standing questions in astrophysics, such as star formation, the life cycle of the ISM, and the chemical evolution of galaxies. As shown in figure 1, ISM structures like giant molecular clouds can subtend hundreds of square degrees on the sky, and have enormous spatial dynamic ranges spanning cloud size structures down to individual protostellar objects. Imaging these clouds requires focal plane arrays of coherent detectors on large telescopes to achieve the required spatial dynamic range while observing molecular gas line emission with sufficient spectral resolution. In astrophysics and remote sensing applications, the speed of imaging a given area of sky is directly proportional to the number of detectors. An increase of a factor of ~1000 in observing efficiency provided by a kilopixel array receiver would revolutionize observational sub-mm/THz astronomy, opening up widefield imaging and dramatically increasing the scientific return of future facilities like CCAT and SPT. Other fields of astronomy went through a similar revolution some time ago. For example, infrared astronomy has graduated from single-pixel technology to arrays consisting of tens of thousands of detectors. The current state-of-the-art pixel count for coherent THz arrays is 64 pixels (i.e. SuperCam) or less. While these instruments are a great leap forward from single pixel detectors, the pixel count is still inadequate for wide field THz imaging of weak spectral lines.

The KAPPa project is developing and testing several solutions to outstanding challenges that must be met if ~1000 pixel THz heterodyne arrays are to be realized. The cost and complexity of such an instrument demand a systematic approach to the solution of these technical challenges before attempting to construct a fully featured science instrument. We are constructing a compact pathfinder instrument with a 16-pixel 2D integrated focal plane at 660 GHz as a vehicle to test technical solutions. These solutions can then be applied to the design and construction of a kilopixel class array receiver. The completed instrument will build on the technology developed for the Supercam project. The instrument will be verified in the laboratory and on the 10m Heinrich Hertz Submillimeter Telescope, making use of existing Supercam [8] infrastructure.

II. Evolution of Coherent THz focal plane arrays

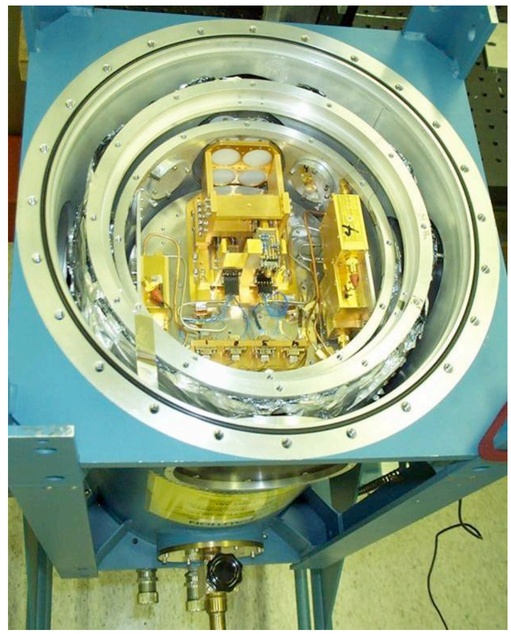

Fig. 2. The PoleStar 4-pixel heterodyne array for the 850 GHz band. The mechanical and electrical complexity of modular components limits pixel number.

A. *0D integrated arrays*

Over the course of the past decade, several research groups around the world have constructed heterodyne arrays for astrophysics applications. The majority of these instruments have been constructed by stacking individual mixers in the focal plane (e.g. PoleStar, [9], DesertStar, [10], HARP-B [11], CHAMP+, [12]). While offering dramatically increased imaging speed over single pixel instruments, the mechanical and electrical complexity of this modular architecture has limited arrays to 16 pixels or less. An example of the mechanical and electrical complexity of such instruments is shown in fig. 2. The PoleStar instrument shown here contains only 4 single ended SIS mixers for the 850 GHz band, with associated cryogenic low noise amplifiers and bias electronics. The mechanical and electrical complexity of the system was due largely to the use of discrete cryogenic DC wiring, semi-rigid coaxial cable for intermediate frequency (IF) transmission, and discrete IF amplifiers. In particular, reliability was compromised by the large number of connectors that required mating and de-mating during construction and maintenance.

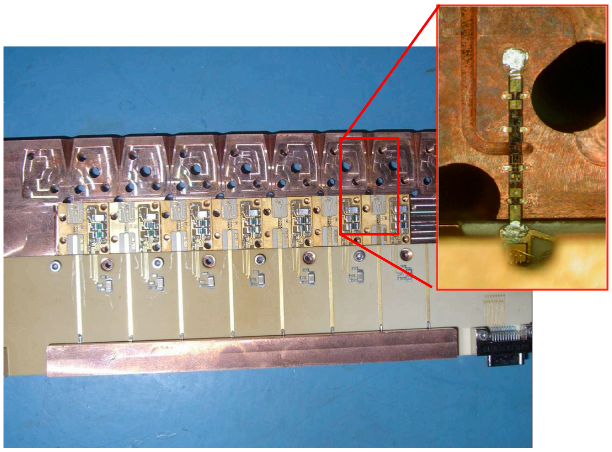

Fig. 3. The Supercam focal plane module with close-up of SIS mixer.

B. 1D Integrated Arrays

Supercam is a 64 pixel heterodyne array receiver designed to perform observations at 350 GHz. Supercam functionally consists of 3 major parts; 1) a receiver frontend, consisting of optics, mixer arrays and a local oscillator that downconverts the 64 incoming 350 GHz signals from the telescope to microwave frequencies and then amplifies them, 2) an IF processor that further amplifies the microwave signals and downconverts them to baseband (0.1 – 1 GHz), and 3) a digital spectrometer that produces a power spectrum of each of the downconverted microwave signals.

At the heart of the Supercam frontend are eight, 1x8 linear mixer modules cooled to 4K in a closed-cycled cryostat. Each split-block waveguide mixer module integrates eight single-ended SIS mixers with eight MMIC-based low-noise intermediate frequency IF amplifiers. The mixer module also contains the associated DC and IF wiring and connectors. Blind mate IF and DC connectors allow the mixer modules to be inserted into and removed from the focal plane without disturbing any cryogenic wiring.

The module, shown in fig. 3, combines many advanced features to maximize performance and reliability. The waveguide module was built to micron level tolerances using an in-house micromilling machine. The SIS devices are fabricated on 3-micron thick SOI membranes, with gold beam lead IF and ground contacts. Eight small beam leads on the chip sides self-align the chip into pockets machined in the waveguide block to a tolerance of +/- 3 microns. A single chip can be mounted and bonded directly to the input matching network of the low noise amplifier in ~15 minutes. The SIS chips have high enough yield and uniformity that cold testing of devices is not needed before mounting. Devices are pre-selected based on their room temperature resistance and are then mounted and cold tested in the focal plane modules. Chips that are found to fail cold testing can be replaced without disturbing neighboring pixels. Each of the low-noise IF amplifier modules contain a MMIC LNA, LNA/SIS bias network, and input and output matching networks. The IF amplifier module package size is 11mm x11mm. Each module offers ~5K noise temperature and 30 dB of gain from 2-9 GHz while dissipating only 8 mW of heat. The high performance of these IF amplifier modules together with their low dissipated power is a key development for heterodyne focal plane arrays. An IF amplifier module and test results are shown in fig. 4.

While considerable effort was invested in the design of the IF amplifier modules and electromagnets (needed to suppress the shot noise resulting from Josephson tunneling in the SIS devices) to lower the power dissipation per pixel, the

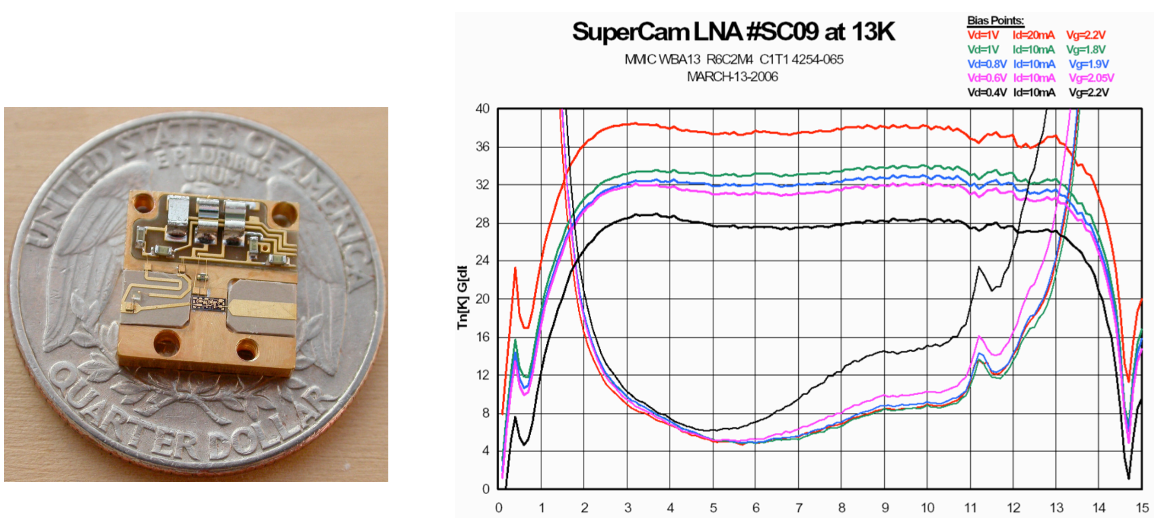

Fig. 4. The Supercam Low Noise Amplifier (LNA) module (left) and test results for 20 mW, 10 mW, 8 mW, 6 mW and 4 mW dissipated power. Noise remains excellent while gain decreases only modestly down to 8 mW power dissipation.

Supercam focal plane still produces over 0.5W of heat at 4K. A commercially available Sumitomo cryocooler with 1.5W capacity at 4.2K is used to cool the focal plane unit. A supplementary CTI cryocooler is employed to cool the 64 IF output cables from the array. This secondary cryocooler permitted standard stainless steel semi-rigid microwave cable to be used for this purpose. The first stages of both coolers are tied to a radiation shield kept at 40K.

LO multiplexing and diplexing is accomplished with a hybrid waveguide/quasi-optical approach. An array of corporate power dividers [13] is employed to split the power from a single Virginia Diodes 350 GHz source 8 ways, feeding splitblock machinable waveguide twists [14]. Additional arrays of corporate power dividers split each of the waveguide twist outputs eight more times before an array of diagonal feedhorns projects the LO beams. A pair of HDPE lenses reimages the array of LO feedhorns to the focal plane of the detectors, using a simple Mylar diplexer for LO injection. The LO power divider has been measured to have ~2 dB loss over an ideal divider. LOs of modest power (<2 mW) are capable of pumping the focal plane array optimally with a 25 micron Mylar diplexer.

III. Challenges for Kilopixel Array Development

During the design phase for Supercam, it became apparent that the expansion of the 0D paradigm of stacking independent mixers in the focal plane would become overwhelmingly complicated and unreliable for ~100 pixel arrays. Similarly, experience with Supercam has shown that the 1D integration of Supercam will also become unwieldy at pixel counts approaching ~1000. We have identified several key areas where technological development is essential to the construction of larger format arrays. These areas and their potential solutions are listed below.

• Mechanical and Electrical Complexity: Larger splitblock based 1D integrated arrays will become too unwieldy to fabricate. Separate interconnect sets are still needed for each linear array.

Solution: Use 2D integration.

• Integration of Detectors with Mixer Module: 2D integration requires a new method for device mounting as compared to 1D splitblock designs.

Solution: Utilize a vertically stacked 2D metal micromachined mixer architecture.

• Economical and fast fabrication techniques for waveguide and feeds: CNC micromachining techniques can make large amounts of waveguide accurately, quickly and economically. Feeds remain difficult to manufacture, especially in large numbers.

Solution: Use a custom tool to directly drill efficient feedorns in metal.

• RF and DC interconnects, wire count, and complexity: At pixel counts of ~1000, individual coaxial transmission lines for each IF signal become overwhelmingly complex and creates an untenable cryogenic heat transfer situation.

Solution: Multi-conductor DC cabling with adequate wire count already exists. Multi-conductor RF ribbon cable and connectors with integral heat sinking should be implemented.

• LO power availability, multiplexing and injection: Kilopixel SIS arrays will require power-combining solid-state multiplier based sources to produce enough LO power.

Solution: Several techniques exist for multiplexing LO power and efficiently injecting that power (e.g. phase gratings, Si Etalons)

• Magnetic field for SIS devices: ~1000 individually controllable electromagnets are unwieldy and too complicated.

Solution: Use carefully engineered high field permanent magnets instead.

IV. KAPPa Demonstration FPU

The KAPPa FPU will be a 16 pixel 2D integrated heterodyne focal plane with integrated SiGe low noise amplifiers (fig. 5). We have chosen the 16-pixel form factor as a reasonable compromise between pixel count (including non-edge pixels) and complexity. The integer multiple of 8 pixels will allow the reuse of Supercam support electronics (bias, IF and spectrometer). Work on the project so far has concentrated on the design and fabrication of components for each pixel cell of the focal plane array. We are reaching completion of the discrete SIS device, and have begun fabrication of test chips to investigate handling and mounting issues. The ultra low power dissipation low noise amplifier chip has been designed, fabricated and tested.

A. Focal Plane Architecture

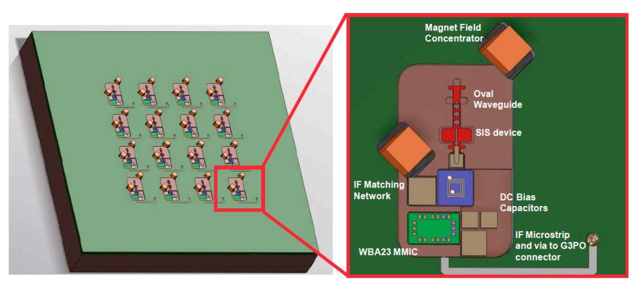

Fig 5. The strawman focal plane array architecture planned for this work. This figure shows the 4x4 detector array at left, with an inset of the detector cell at right.

We have chosen to use discrete SIS detector chips for KAPPa. This extracts the maximum from existing wafer yield, and uses the wafer area most efficiently during fabrication. Experience with Supercam has shown that beamlead based pixels can be assembled in as little as 15 minutes, making assembly of even 1000 discrete detector pixels feasible. Initial focal plane designs, plus the desire to remain compatible with the Supercam optical system on the HHT, have resulted in the selection of a 6 mm pixel pitch for our prototype array. Since our SIS devices are fabricated on 50mm wafers, the area required for a 4x4 array is very large (almost an entire wafer). This could result in very poor detector array yield and poor uniformity over the large wafer area. Discrete detectors will allow close packing, with hundreds of devices per wafer. With this large number of available devices, variations across the wafer will have a smaller impact on usable chip yield.

The all-metal machined mixer block uses a skeleton printed circuit board to route IF and DC lines. The KAPPa FPU design integrates the SIS device, low noise amplifier MMIC (both discussed below in detail) and associated lumped element components in a pedestal machined into a copper block. A Rogers TMM based printed circuit board with cutouts for the pedestals will carry DC bias lines from edge connectors to each pixel. A microstrip line carries the amplified IF signal to a via, which transfers the IF to a surface mount Corning-Gilbert G3PO blind mate connector on the back side of the PC board. These connectors protrude through holes in the copper block, and mate with an additional PC board made of the same TMM material, also with surface mount G3PO connectors. This arrangement transfers the IF to a different plane to allow easy routing of the IF lines from all pixels without the need to avoid other pixel pedestals or DC traces. These boards will also contain the connectors for attaching to the flex circuits that will be used to route IF and DC signals out of the cryostat.

We will investigate spring contact interposer connectors for both DC and IF flex circuits, but will use direct wirebonding if the interposers do not work as planned. Rather than develop some sort of interconnect at the vacuum wall of the dewar, we will pot the flex circuits directly in epoxy, running them unbroken through the dewar wall. We plan to use a stripline architecture for the flex circuits to avoid interaction with the epoxy potting.

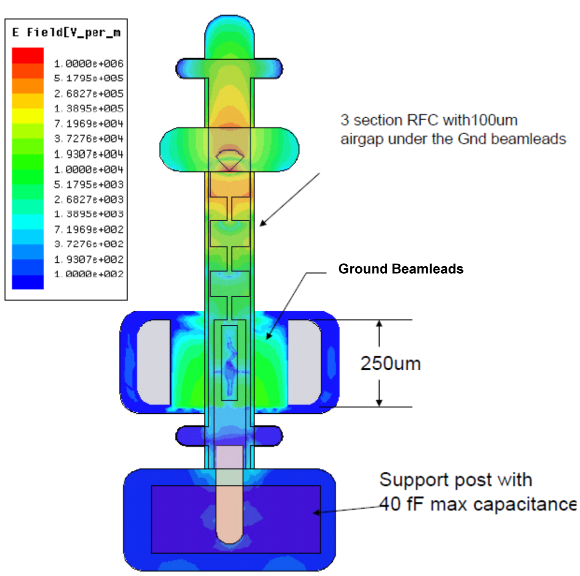

Fig. 6: The SIS device design showing a HFSS simulation of the RF E-field. The choke structure effectively prevents RF leakage.

B. SIS device

For this project, we have chosen to follow the heritage gained from the Supercam in designing the discrete SIS device. Our experience from Supercam has shown that SIS devices fabricated on SOI membrane are robust and easy to mount. We have refined the Supercam design for this work to improve the ease of mounting and handling while still maintaining optimal performance. We have chosen to baseline a relatively simple single junction design using a traditional AlOx barrier. This will maximize chip yield with the relatively high Rn required to match to the integrated low noise amplifier discussed below. An AlN barrier would provide wider RF bandwidth, but would require very small junction areas for an Rn~30 as desired. This could reduce chip yield to unacceptable levels. In addition, AlOx barriers provide sufficient bandwidth to cover the 450 micron atmospheric window. Additional bandwidth is not required.
The chip will be fabricated on 5 micron thick SOI membrane. EM simulations have shown that this is the thickest SOI permissible without degradation of performance. The SOI membrane will be patterned to provide mechanical alignment tabs for chip mounting. In the Supercam device, we used beam leads for this purpose, but we believe using the silicon itself will result in more robust devices. Beam lead tabs with rounded corners will be used for ground and IF contacts. As with Supercam, the device will use a radial stub waveguide probe with a multi-section RF choke. Unlike Supercam, the IF and ground are on the same side of the probe, eliminating the need for a meandering high impedance line to serve as a ground return path. This meandering line causes resonances that limit the RF bandwidth. These are tolerable for the lower frequency Supercam devices, but not for this work. The IF will be brought out on thin film microstrip fabricated on top of the RF choke structure that serves as the ground plane. This does result in increased potential for reduced chip yield, but does not require any additional layers in the fabrication.

C. Low Noise Amplifier

KAPPa will integrate a MMIC low noise amplifier directly into the mixer FPU. The amplifier is based on Silicon Germanium (SiGe) technology, and has been designed for ultra-low DC power dissipation. An integral, on chip bias tee used to inject DC bias without a bulky circuit based on discrete components. This amplifier was designed to provide 16 dB of gain and ~7K noise temperature from 0.5-4.5 GHz while consuming only 2 mW of DC power. The devices have been fabricated as part of a wafer run at ST Microelectronics. The first run of devices works as expected; with the exception of somewhat elevated noise at 4K (12K rather than ~7K). We expect he next generation of chips (now in fabrication) to reduce the noise to the design value.

A simple matching network consisting of a surface mount chip inductor in series with the detector matches the LNA to the SIS device. This results in performance that is not sensitive to SIS device normal resistance from 50-200 ohms. Future generations of this chip can be fabricated to include the matching inductor. This route allows the maximum flexibility to use the chip in the largest number of applications.

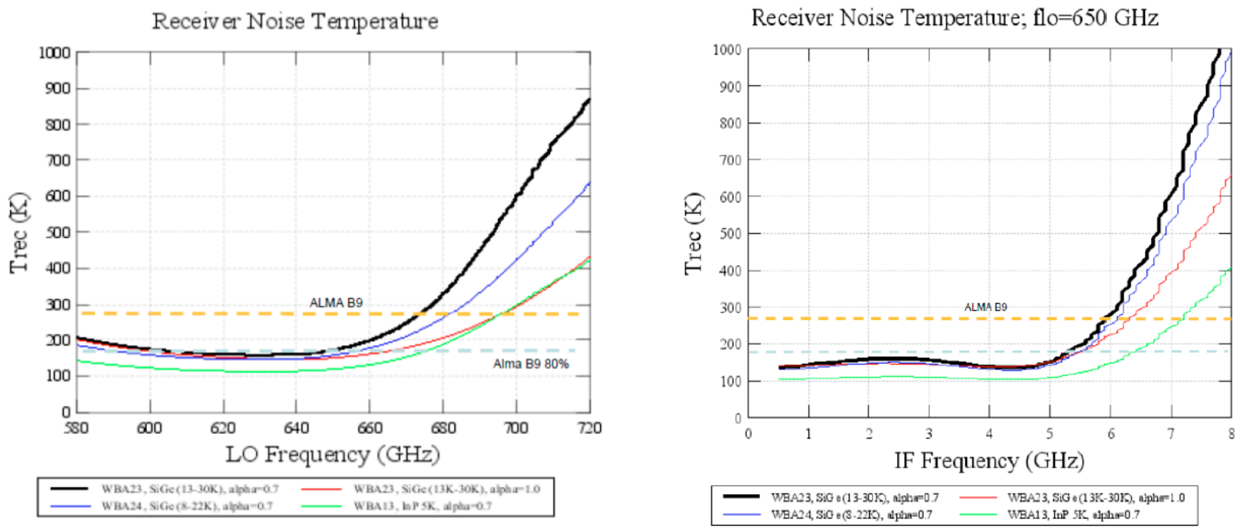

Fig 7. Simulated RF performance of the mixer versus LO frequency (left) and IF frequency, with a LO frequency of 650 GHz (right). The 4 curves show performance for two amplifier designs (the WBA23 is the KAPPa device) and with two LO pumping levels. Alpha=1.0 is optimal pumping, alpha=0.7 is 70% of optimal pumping, The design meets ALMA Band 9 specifications for most of the band using the WBA23 LNA with optimal SIS device pumping.

D. *Simulated Performance.*

We have built a comprehensive performance model of the KAPPa pixel, including estimates for optics loss, SIS device performance, matching network and low noise amplifier. We have assumed a 3% loss at room temperature for the LO diplexer and window, and another 3% loss for IR filtering. We are currently using the measured noise performance of the existing LNAs (12K) in our models. Results are presented in fig. 7. We find that the KAPPa mixer is predicted to meet or exceed ALMA Band 9 noise specifications from below 600 GHz to 695 GHz. The rapid rise at the high end of the band is due to loss in the niobium transmission lines as the RF exceeds the gap frequency of the material. IF performance is predicted to be approximately flat between 0.5 GHz and ~5 GHz. This 4.5 GHz IF bandwidth is more than adequate for almost all wide field imaging science applications (even for extragalactic sources).

V. Future Work

Now that the design and fabrication of the SIS device and LNA are well underway, and a viable design for the focal plane has been designed, we will next concentrate on the design and fabrication of a single pixel test mixer that will allow us to analyze and refine the design for the pixel cell. This single pixel mixer will also be used as a testbed to develop the permanent magnet used to replace tunable electromagnets. The single pixel mixer will allow the use of the well-characterized electromagnet from the Supercam project, and a permanent magnet assembly that has been engineered to deliver the same field as the electromagnet under optimum performance. Our simulations show that commercially available 1.5mm diameter, 1.5mm long cylindrical electromagnets, combined with a simple iron concentrator, can deliver similar fields to the Supercam electromagnet with 20 mA of current in 4500 turns of wire.

VI. Conclusion

The Kilopixel Array Pathfinder Project (KAPPa) is a project to construct a 16-pixel 2D integrated coherent focal plane unit as a demonstration of necessary technologies needed for the construction of kilopixel class arrays for large terahertz telescopes. The design of KAPPa builds on experience gained building the Supercam 64 beam array, which uses 1D integrated linear detector array modules. The KAPPa focal plane will use beam lead on SOI SIS devices, integrated SiGe MMIC low noise amplifier chips with on-chip bias tees, drilled smooth walled feedhorns, permanent magnets and IF flex circuit cables to solve many of the challenges presented in building very large coherent arrays. We will build and test a single pixel demonstration mixer to verify the performance of the mixer cell before constructing the 16-pixel array. We will then incorporate the lessons learned from this test into the design of the FPU.

Acknowledgment

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