An SIS mixer based focal-plane array at 230 GHz

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Abstract— **Efficiently mapping large areas of the sky with high spectral resolution at mm and sub-mm wavelengths will require a new generation of heterodyne focal-plane array receivers. The number of pixels in such arrays has not increased particularly rapidly in the last two decades, with maximum achieved pixel numbers between 16 and 64 (e.g. [1] and [2]). Thus new approaches are needed to address such problems as local oscillator (LO) injection, feed horn fabrication and SIS mixer design, fabrication and repeatability.**

Here we describe a prototype focal-plane array unit based on unilateral finline SIS mixers, fed with smooth-walled feed horns. LO injection power diplexing is achieved by a combination of directly machined waveguide Y-power splitters and bow-tie cross waveguide couplers. The 1×4 prototype array, currently under construction, will demonstrate several technologies relevant to the construction of large format arrays.

I. Introduction

The physical and chemical conditions within star-forming regions can be determined astronomically by observing submillimetre-wave spectral lines. Important transitions include the $J \rightarrow J+1$ lines of CO (and isotopomers), HCN, HCO+ and the redshifted fine-structure lines of [CII] and [NII]. Making deep maps of these spectral lines in spatially extended ($\sim 1 < \theta < \sim 100$ arcmin) regions within our own Galaxy using interferometers, such as ALMA, is difficult due to their inherently small field of view. Since SIS mixer based heterodyne detectors between 100 GHz and 1 THz are now approaching sensitivities of only a few times the quantum limit, the only remaining way to greatly increase mapping speeds is to integrate more detectors into the focal-planes of large single dish telescopes.

At millimetre and submillimetre wavelengths, we can now build bolometric focal plane array cameras with many thousands of elements [3]. However, if we require medium to high spectral resolution to study the intensities and kinematics of spectral lines, heterodyne detectors based on SIS mixers coupled with digital spectrometers remain the technology of choice. Unfortunately, integrating more than a few tens of detectors into focal-plane array receivers has remained challenging. There are several main technical reasons for this:

(i) Large numbers of high quality feed horns (traditionally electroformed corrugated horns) are expensive and time-consuming to construct in quantities of more than a few tens of horns.

(ii) As well as efficiently coupling the sky signal into each SIS mixer, we must also divide an LO signal and couple it to each mixer in the array.

(iii) For quasiparticle SIS mixers, we must apply a magnetic field of an appropriate strength to each tunnel junction to suppress the unwanted Josephson tunnelling of Cooper pairs.

(iv) We must arrange for the independent DC biasing of each mixer chip.

(v) For each mixer, we must amplify the down-converted IF signal with a state-of-the-art low noise cryogenic amplifier, and ensure that the IF signal is well matched to the input of impedance of this amplifier.

Each of these complications, combined with factors such as the costs of large cryostats and high throughput digital spectrometers, have acted to limit the number of SIS mixer based pixels in focal plane array receivers. The astronomical motivations for building large format heterodyne focal plane arrays have been clear since the mid-1990s [4], but relatively few complete receivers have been developed, with pixel counts of ~16 achieved in the early 2000s (e.g. [1]) with a small number of receivers with pixel counts of between 16 and 64 currently in development or recently completed [2][5]. There is therefore a clear need for technological development in this area. In this paper we will describe a heterodyne array receiver prototype for use at frequencies between 200 and 280 GHz, which will act as a demonstrator for several technologies which can, in principle, be scaled up to receivers containing between 100 to 1000 elements

II. Focal Plane Array Concept

A diagram of the 3D solid model for our heterodyne array prototype is shown in Fig. 1. Our initial proof-of-concept array will consist of only four SIS mixers, limited by our test cryostat size, but we hope to demonstrate several technologies which can be scaled up to much larger arrays. In a final instrument, the linear $1\times N$ array blocks like the one described below will be stacked to give a rectangular $N\times N$ focal plane array.

The sky signal will be fed into the mixer block in Fig. 1. via a single block of drilled, smooth-walled horns described in Section III below. Each horn will couple radiation into each of the four input waveguides of the mixer block (Fig. 1, (d)). The sky signals are then coupled onto the SIS mixer chips which will initially be fabricated on a quartz substrate, with a view to incorporating Silicon-On-Insulator (SOI) substrate mixers in the near future. The design of these SIS mixer chips are described in more detail in Section IV below. Bond wires then couple the IF signal onto an IF matching board, which is positioned in an IF board pocket (Fig. 1, (n) and (o)) fabricated at right angles to the plane of the mixer chip. This geometry allows the LO signal to be coupled to each mixer chip using a waveguide based diplexer (Fig. 1, (e) and (i)) which occupies a single plane within the split block structure.

The LO signal is introduced into a waveguide which feeds into the side of the mixer block (Fig. 1, (a)). It is then split into four using three -3dB E-plane waveguide splitters (Fig. 1, (e) and (i)). The LO signals are then coupled into each waveguide feeding each mixer chip by -17dB coupling structures each consisting of three bow-tie antennas positioned in cross-waveguide slots (Fig. 1, (h) and (l)). The components of the LO coupling structure are described in more detail in Section V below.

The IF signals are coupled out of the mixer block by SMA connectors soldered to IF matching boards (Fig. 1, (o) and (p)). In the prototype, a commercial bias-T will be connected to each IF output to transmit the IF signal and allow DC biasing of the mixer chip. A magnetic field is applied to each mixer using a traditional superconducting magnetic coil, which uses a magnetic circuit consisting of soft iron pole pieces (Fig. 1, (c)) and end shoes (Fig. 1, (g) and (k)) to concentrate the magnetic field near the SIS junction. This enables a sufficiently strong field to be generated without the need for large coil currents which can cause problems with local heating in the non-superconducting wiring connected to the superconducting winding of the coil. This magnetic circuit should also enable the relatively straightforward investigation of the suitability of the use of permanent magnets [6] to suppress Josephson tunnelling using small modifications to the current prototype.

III. Smooth Walled Feed Horns

Corrugated horns, usually manufactured by electroforming, are most often used as feeds for mm and sub-mm instruments. However such horns are expensive and time consuming to produce and this becomes a significant problem as the number of feed horns required in the focal plane increases above a few tens of horns. For our prototype, we will use multiple flare angle smooth-walled feed horns directly machined into a single block of aluminium with a shaped machine tool (Fig.2).

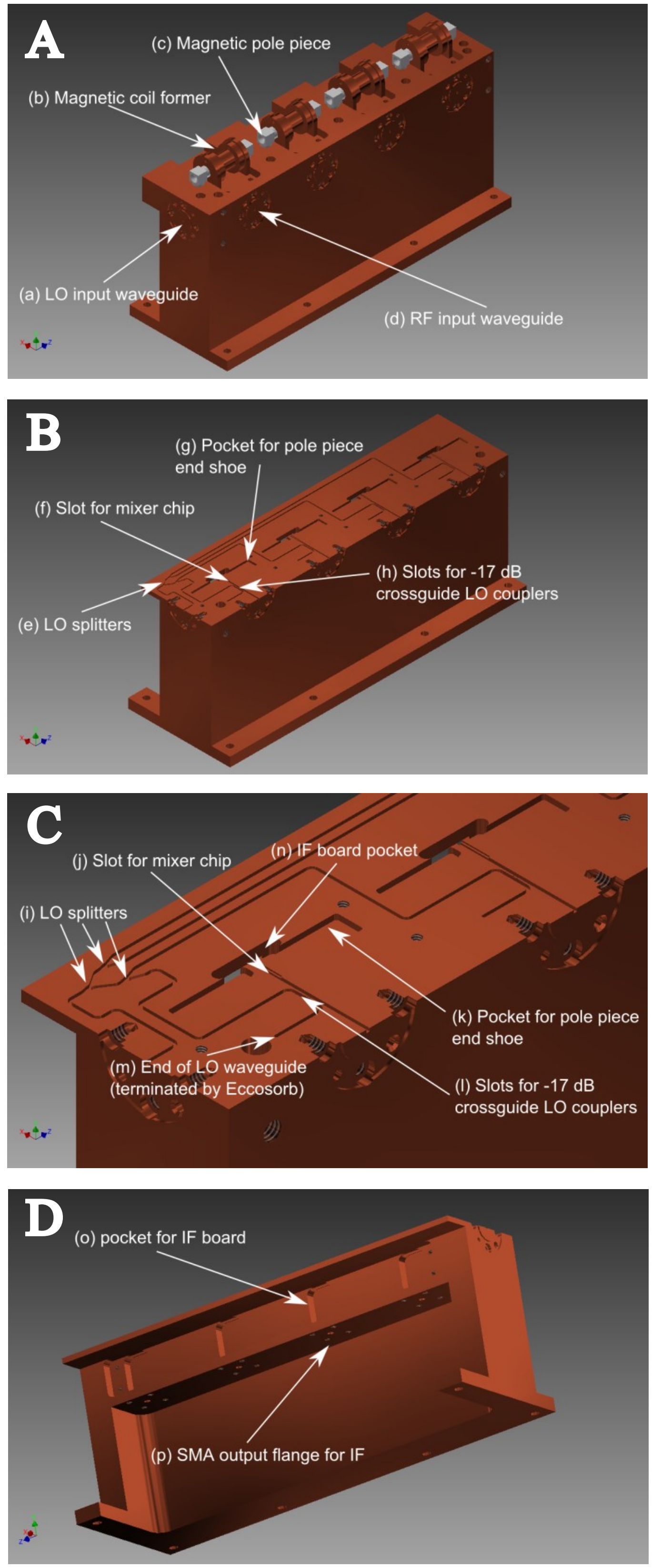

Fig.1 (A) Solid model of the assembled mixer block. (B,C) Detail of the lower half of the mixer block, showing the waveguides and slots for the SIS mixers and the LO injection structure. (D) The rear of the mixer block showing the IF board pockets machined at a right angles to the plane of split in the split block.

In previously reported work [7], we have described the design process for these horns, which use a genetic algorithm (GA) and modal matching to optimise the positions of several flare angle discontinuities to give a far-field pattern with high beam circularity and low cross-polarisation. The relatively simple interior profile of these horns means that large arrays of these horns can be manufactured rapidly and cheaply by using a shaped machine tool to repeatedly drill into a single block of aluminium. Using this technique, we have successfully manufactured and experimentally tested individual horns at 230 GHz and 700 GHz, as well as a 37 horn array prototype [8]. For our prototype we will use a 1×4 horn array drilled into a single block, with a separate block consisting of directly machined rectangular-to-circular waveguide transitions. Such horn arrays will enable much larger format horn arrays to be fabricated at a small fraction (~10%) of the cost and time required to manufacture electroformed corrugated horns.

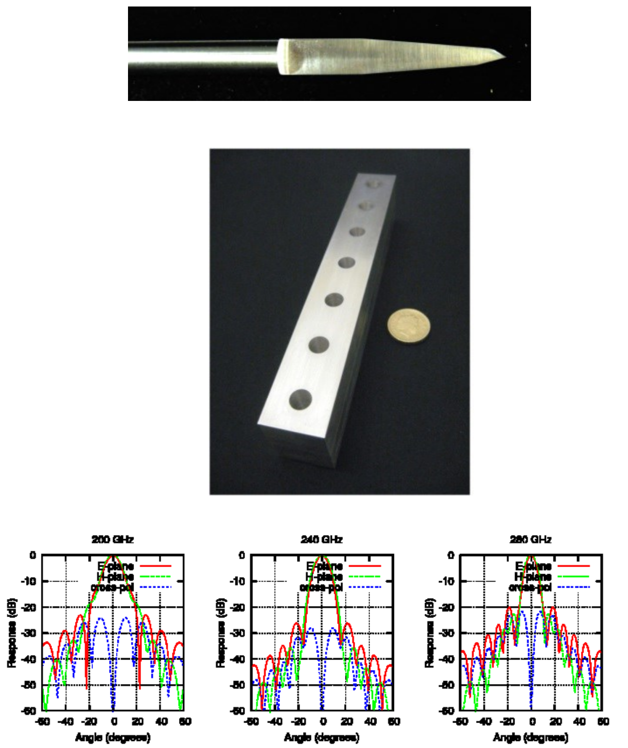

Fig. 2 (Upper) Shaped machine tool used for direct “drilling” of feed horns. (Middle) A 1×7 array of smooth walled feeds drilled into a single aluminium block. (Lower) Calculated beam patterns for a 2-Section smooth walled horn at 230 GHz with 33% fractional bandwidth.

IV. Unilateral Finline SIS Mixers

At Oxford, we have an extensive development programme of finline-based SIS mixers for 230 GHz, 680 GHz and into the THz regime. Our research focus for our low frequency (230 GHz) SIS mixers has been extending the available IF bandwidth of the SIS mixers [9]. Our SIS mixers (Fig. 3) couple radiation from the waveguide using a unilateral finline structure. This is followed by a novel slotline-to-microstrip transition which couples the radiation to a microstrip. A wide RF bandwidth tuning circuit tunes out the parasitic capacitance of the SIS junction. This comprises of a 3-stage Chebychev transformer, a double-stub inductive tuner before and after the SIS junction and an RF choke. The RF choke prevents leakage of the RF signal into the IF passband, and the entire tuning structure has been carefully optimised using HFSS modelling to minimise the capacitance at IF frequencies and thus maximise the useable IF bandwidth. We have tested mixers with state of the art (T_{sys} < 60 K) performance using a 10 GHz IF bandwidth, and our current design is expected to offer good performance over an IF band of 2 to 16 GHz. A batch of these mixer chips is currently being fabricated at LERMA, Paris Observatory.

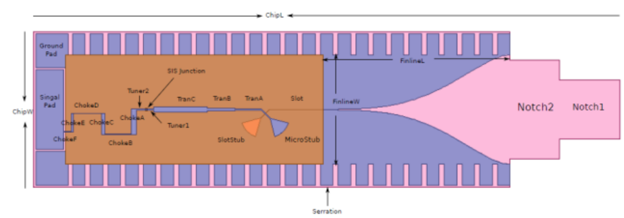

Fig. 3 The unilateral finline 230 GHz SIS mixer chip showing the unilateral finline and slotline-to-microstrip transition and tuning circuit to give wide RF and IF bandwidths.

V. Local Oscillator Injection

The local oscillator signal will be injected into a rectangular waveguide at the side of the array block, and then split using a tree of directly machined E-plane Y-shaped power splitters. The design of these splitters in illustrated in Fig. 4 and the simulated HFSS performance is shown in Fig. 5.

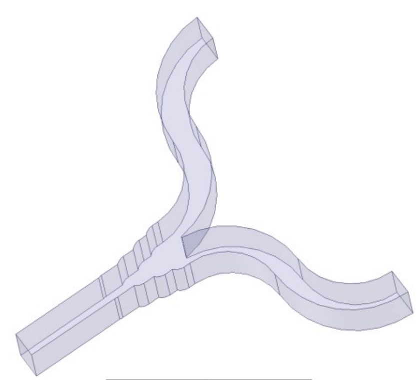

Fig. 4 Design of -3dB E-plane power splitters.

After the LO power is divided equally into 4 parts, cross-guide waveguide couplers are used to couple 2% of the divided LO power into the waveguide in front of the SIS mixer chip. These waveguide cross couplers consist of three bow-tie antennas fabricated on quartz substrates, arranged as shown in Fig 6. The unused LO power is absorbed at the end of the waveguide by a tapered piece of machined Eccosorb. The

HFSS simulated performance of these couplers, and experimental measurements, are shown in Fig. 7. We have previously successfully fabricated and used these cross-guide couplers in single mixer blocks [10] and they have been shown to function well, although with a ~3 to 5 dB higher coupling than the HFSS simulations. We are currently investigating the possible causes of this higher coupling.

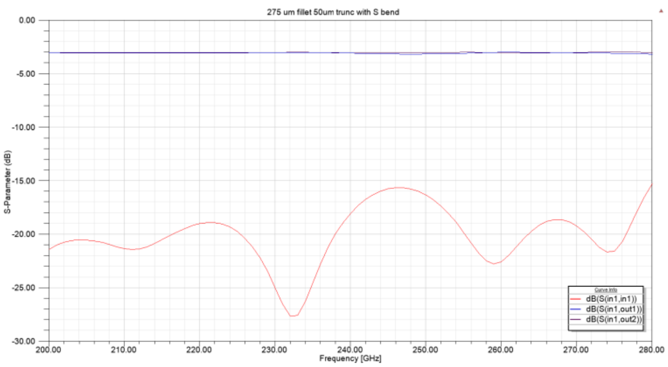

Fig. 5 Simulated performance of the -3dB E-plane power splitters, showing very even power -3 dB power splitting (blue and brown lines) and low return loss (red line) over the 200 to 280 GHz bandwidth.

VI. Conclusions and Future Work

The prototype mixer block and feed horn array is currently being fabricated at Dept. of Physics, University of Oxford and the Rutherford Appleton Laboratory. A new batch of SIS mixers of the design described above are currently being fabricated at LERMA, Paris Observatory. We intend shortly to install the complete prototype in a test dewar and measure hot/cold noise temperatures within the next few months. In parallel with this work, a 200-280 GHz LO source based on a ×12 multiplier chain is currently being developed by colleagues at the Rutherford Appleton Laboratory [11] to enable testing the complete LO injection unit. Future development in this area will include construction of a full 8×8 array prototype and also array development at higher frequencies such as 680 GHz.

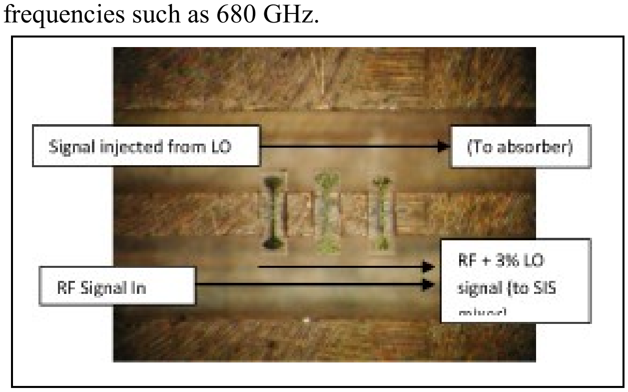

Fig. 6 Photograph of the cross-guide LO coupler chips mounted between two waveguides in a mixer block.

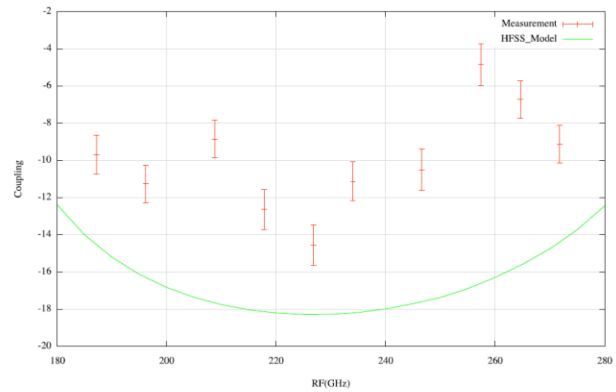

Fig. 7 Simulated (green line) and measured (red error bars) performance of cross-guide LO injection couplers.

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