Development of Millimetre-Wave Heterodyne Array for Airborne and Space Satellite Mission

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***Abstract*—In this paper, we present our latest works on developing the various generic technologies to find the innovative solutions for constructing a heterodyne focal plane array, based on the Superconductor-Insulator-Superconductor (SIS) mixer technology. This includes the use of the planar superconducting circuit technology to replace the commonly used bulky waveguides or optical components, therefore simplifying the radio frequency (RF) operation and minimising the size of the array. We will describe the design of a novel easy-to-machine feed horn technology which enables deployment of large arrays with minimal cost. This technology has been demonstrated successfully and has since been deployed in various existing and up-coming telescopes. We then demonstrate these capabilities by presenting the design and built of a small pixel-count array near 220 GHz range, combining both the E- and H-polarisation chains within a single mixer block. Finally, we briefly describe our recent works on the superconducting parametric amplifier technology that could potentially replace the conventional semiconductor amplifiers that are power hungry and dissipate large amount of heat, which render the construction of large arrays difficult.**

***Index Terms*—Millimetre technology, superconductor-insulator-superconductor (SIS) mixer, feed horn, amplifier, astronomical receivers**

I. INTRODUCTION

One of the main limitations in current millimetre (mm) and sub-mm astronomy is the capability to map large structures of the nearby Universe with a high spectral and spatial resolution, and with a fast observation speed. The latter requirement is driven by the fact that for operation near the THz regime, even the driest locations on Earth would only have a limited amount of high quality weather for observation. Space-borne observatories above Earth's atmosphere, such as the high-altitude balloon/flight operations or space satellite missions, would not have such issue but they tent to have limited lifetime before the mission ceases to operate at the required condition. Therefore, it is paramount to maximise the scientific outputs of these observatories by mapping a larger area of the sky simultaneously.

The most straightforward way to increase the mapping speed is to deploy a large pixel count receiver. Unfortunately, most of the existing mm/sub-mm facilities are still equipped with only a single-element dual-polarisation receiver, except for large single-dish telescopes such as the James Clerk Maxwell Telescope (JCMT) and the Fred Young Submillimetre Telescope (FYST), which starts to incorporate small singly-polarised array by simply duplicating and stacking several of the single-pixel linear receivers together to form an array [1]–[3]. Most of these deployments are possible because of the large estate available at these large ground-based facilities, which could not be applied to space-borne missions due to their weight, power and spacial constrains. To lift this predicament, one needs to develop a different technologies for constructing large array which is compact and light-weight. This is important not only for space-borne mission, but also for ground-based interferometric facilities such as Atacama Large Millimetre/sub-mm Array (ALMA) and Northern Extended Millimetre Array (NOEMA). This is because the construction of these large interferometers are costly and time/labour intensive, hence it is not expected that there will be any major new construction large facilities in the foreseeable future. Hence, the developed array technologies must be able to fit into the current spacial constrains of these existing facilities to upgrade the capabilities of these important instruments.

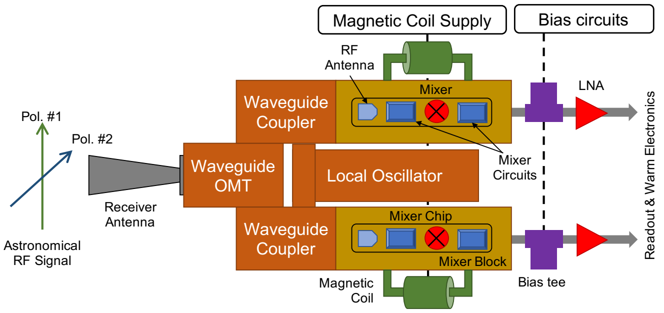

Fig. 1. Diagram showing the architecture of a conventional dual-polarisation heterodyne superconductor-insulator-superconductor (SIS) receiver which requires five interfaces to provide access for the astronomical radio-frequency (RF) signal, the local oscillator (LO) signal, the magnetic coil wiring for suppressing the unwanted Cooper pairs tunnelling, wiring to DC-bias the SIS mixers, and for readout of down-converted intermediate frequency (IF) signal. The waveguide othormode transducer (OMT) can be replaced with wire grid or diplexers but would complicate the receiver optics.

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However, it is still technically challenging to deploy a compact large pixel count heterodyne array while maintaining the quantum limited sensitivity of the receiver in the THz regime. This is because the construction of even a single-pixel dual-polarised SIS receiver is rather complicated, requiring the injection of the local oscillator (LO) signal along with the RF signal from the sky via a feed horn, application of magnetic field to suppress the unwanted Cooper pair tunnelling, direct-current (DC) circuitries to bias the mixer, as well as the readout of the down-converted intermediate frequency (IF) signal, before further amplification with a cryogenic low noise amplifier (LNA).

Conventionally, these components are constructed using waveguide technologies, as shown in Fig. 1, resulting in a bulky and irregularly shaped receiver structure. Although some of these waveguide pieces can be substituted with other types of optical components, such as using a beam combiner to replace the waveguide coupler, but this often come with a cost of complicating the optical design of the receiver. Furthermore, it is impractical to directly extending the construction of these receivers into an array, because it would be difficult to stack them together either vertically and/or horizontally. In this paper, we briefly introduce our efforts in simplifying the receiver architecture using various innovative technologies such that the construction of compact large array would be feasible in the near future.

II. MULTIPLE-FLARE ANGLED SMOOTH-WALLED HORN

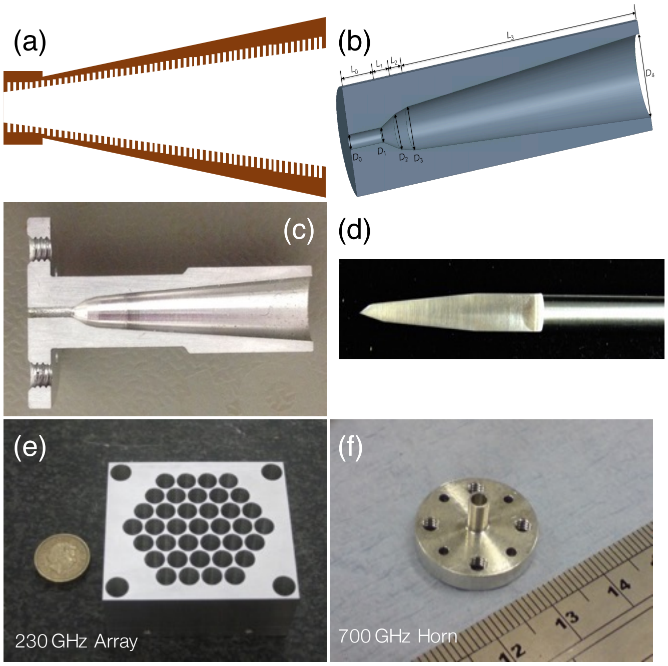

Fig. 2. (a) Sketch showing the cross-section drawing of a corrugated horn. (b) Sketch of a multiple-flare angled smooth-walled horn. (c) Photo of a fabricated 230 GHz smooth-walled horn split into half to show the internal wall profile. (d) The drill bit used to fabricate a smooth-walled horn. (e) A fabricated 37-horn array using the smooth-walled horn technology. (f) A fabricated 700 GHz smooth-walled horn.

In a mm/sub-mm heterodyne receiver, it is common to use a feed horn to couple the RF and LO signal into the mixer block, due to its excellent far field beam configuration that can be easily designed to match the telescope's optics. Traditionally, this is achieved by using a corrugated horn [4], as shown in Fig. 2 (a), which make use of a series of corrugated rings milled into the inner wall of the horn to suppress all the unwanted modes and preserve a uniform and well-controlled beam profile. However, it is difficult and costly to manufacture these types of feed horn due to the need of the large number of dense corrugations of small dimension and with high accuracy, especially near the throat of the horn and at higher frequencies.

In order to avoid the need for these corrugations, we instead create a series of discontinuities in the inner wall of our feed horn by changing the flare angle of each conical sections (see Fig. 2 (b) & (c)) to generate higher order modes inside the horn [5]–[7]. By carefully choosing the lateral positions and the height of these discontinuities (i.e., the flare angle) to produce a combination of all modes in the horn that resembles the same field configurations as the corrugated horn at the aperture of our horn. In this way, we reproduce the same far field beam pattern similar to that of a corrugated horn, but without the need of any corrugations, hence simplifying their construction. These multiple-flare angled smooth-walled horns can be easily fabricated using a shaped tool shown in Fig. 2 (d), drill directly into a metal piece. The same tool can also be used to repeatedly drill into a larger piece of metal to form an array as shown in Fig. 2 (e). This technology is now used widely in many astronomical receivers, ranging from several hundred GHz up to a few THz (see Fig. 2 (f)).

III. SIS MIXER ARRAY

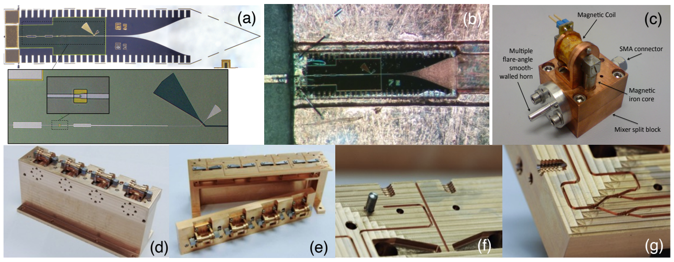

Fig. 3. (a) A superconductor-insulator-superconductor (SIS) mixer chip fed with a unilateral finline antenna, with zoomed-in images showing the mixer circuits and the tunnel junction. (b) A fabricated mixer chip mounted along the waveguide section of the mixer block. (c) Mixer block equipped with the RF feed horn, magnetic coil and IF connectors for readout. (d) & (e) Photo showing a 4-pixel SIS mixer array. (f) Zoomed-in image showing the structure of the waveguide coupler and (g) the local oscillator (LO) waveguide distribution network.

Fig. 3 (a) & (b) show the example of an SIS mixer chip comprising a unilateral finline RF antenna, an impedance transformer circuit, a tunnel junction for signal down-conversion, and an RF choke for optimal power coupling [8], [9]. Similar to other types of SIS mixer chips utilising different antenna (e.g., [10] & [11]), these mixer chips generally would be aligned and mounted in the rectangular waveguide section of a mixer block (Fig. 3 (c)) that connects to the output of the feed horn via a circular-to-rectangular waveguide transition. These singly-polarised mixer block can be further combined to form a dual-polarisation receiver using either a waveguide othormode transducer (OMT) or an optical beam diplexers. They can also be extended to form a linear $1\times N$ array as shown in Fig. 3 (d–e) with additional waveguide network for LO coupling and distribution (Fig. 3 (f–g)). However, forming a dual-polarisation receiver or array by simply duplicating and extending the similar block structure often resulting in bulky and inefficient construction. It is also difficult to construct an $N \times N$ array using this method due to the limited access interfaces, especially for pixels near the centre of the array which would only have the front and back interfaces where all the side walls would be blocked by the adjacent pixels.

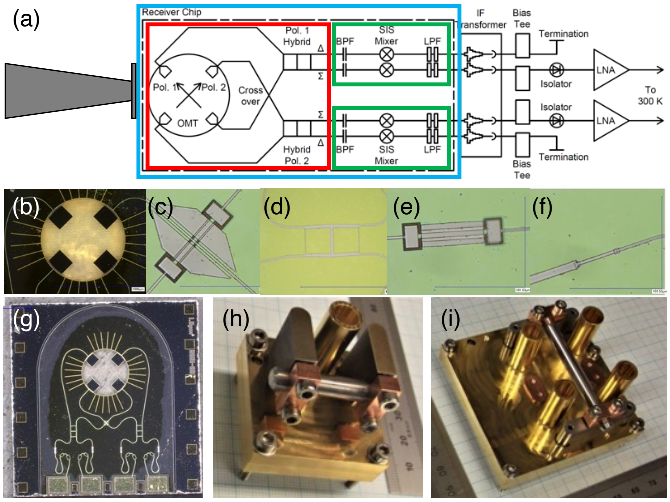

Fig. 4. (a) Schematic of an on-chip dual-polarisation superconductor-insulator-superconductor (SIS) receiver. (b) The planar orthomode transducer (OMT), (c) the cross-over, (d) the quadrature hybrid, (e) the DC-block and (f) the mixer circuit that form (g) the mixer chip. (h) The mixer block housing the mixer chip. (i) A compact 4-pixel dual-polarisation mixer array.

In order to simplify the architecture of the receiver, we opt to replace most of these waveguide components with planar superconducting circuit components [12], [13]. First, we combine the two individual polarisation chain into one using a compact planar orthomode transducer (OMT) instead of the large waveguide OMT or optical diplexer. Fig. 4 (a) shows the schematic diagram of the dual-polarisation receiver. All the required circuit components such as (b) the planar OMT, (c) the cross-over, (d) the quadrature hybrid, (e) the DC-block and (f) the mixer circuit are now all formed using planar superconducting circuit technology and deposited directly onto (g) the mixer chip itself. This results in a compact and elegant mixer chip sizing only 4×4 mm for a 220 GHz device, which can be mounted within a single mixer block without any other waveguide components.

This approach allows us to drastically simplify the construction of the mixer block, which now requires only a direct drilling of the smooth-walled horn without the need of any waveguide transitions. As shown in Fig. 4 (h), the simplicity of the mixer block in which all the four side interfaces are now free of any obstruction, hence could be easily extending into a large array by replicating the block architecture and populating the mixer chips along the array (Fig. 4 (i)). A similar approach of using planar circuit technology to form multi-pixel heterodyne array can also be found in [14], [15].

IV. SUPERCONDUCTING TRAVELLING WAVE PARAMETRIC AMPLIFIERS

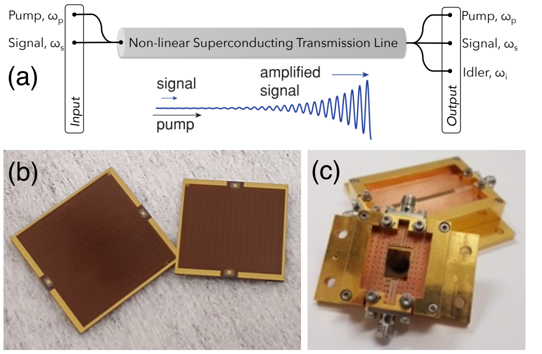

Fig. 5. (a) Diagram showing the working principle of a travelling wave parametric amplifier (TWPA). (b) The fabricated TWPA chips. (c) TWPA chips mounted in the sample box.

The final component of a heterodyne receiver before the room-temperature electronics is the cryogenic LNA to read out and amplify the down-converted IF signal for further processing. Typically, the hot electron mobility transistor (HEMT) amplifiers are the preferred choice of such LNA due to their broadband and low noise characteristic. However, even the state-of-the-art HEMT amplifiers are still incapable of achieving the ultimate quantum-limited noise performance. More importantly, they are often power hungry and dissipate a large amount of heat, making their deployment for large array difficult as they require order of magnitude higher power and cooling requirement compared to a single-pixel receiver. This is especially detrimental for air-borne mission where both the power and cooling capacity are rather limited by the estate of the satellite.

In recent years, there has been a lot of effort in trying to find a solution to replace these semiconductor amplifiers. Travelling wave parametric amplifier (TWPA) is a recently developed technology that could potentially achieve broadband amplification with the required quantum limited noise amplification and with negligible heat dissipation, hence could replace the HEMT amplifiers for the array application. As shown in Fig. 5 (a), a TWPA operates by injecting a strong oscillating ‘pump’ signal along with the detected weak RF signal in a highly nonlinear medium, and achieves signal amplification via wave-mixing mechanism that transfer the energy from the pump to the weak signal. Generally, the nonlinear medium can be formed using a high kinetic inductance superconducting film [16], [17] or utilising the nonlinear inductance of a series of Josephson junctions [18], [19]. As the wave-mixing is performed through the nonlinear reactance of the medium, and that these superconducting material have negligible resistivity, the heat dissipation is therefore minimal. Fig. 5 (b) & (c) show the TWPA chips we developed recently, which we expect to have approximately 20 dB parametric gain from 3–9 GHz. As shown in the figure, the construction of these TWPAs is also in the planar circuit form, hence it holds the potential for further integration with the detector circuit e.g., the SIS mixer circuit, as well as forming an array of amplifier with a single chip, further simplifying and minimising the real estate of a mixer array. Although the development of this TWPA technology is still in its early stage, it is crucial for the deployment of large heterodyne and bolometric array without compromising the IF bandwidth performance, nor complicating the cryogenic system construction. It could even improve the array sensitivity with its quantum-limited noise performance.

V. CONCLUSION

In this paper, we briefly summarise the three main technologies that we are developing in order to improve the construction of a large heterodyne array. These includes the use of a smooth-walled horn to replace the conventional corrugated horn, and the potential use of the superconducting parametric amplifiers to replace the HEMT amplifiers in order to minimise the power and heat dissipation requirement for a large array. To reduce the size of the receiver array, we further form a majority of the required receiver circuit components on-chip using the planar circuit technology to dramatically simplify the receiver block design, therefore make feasible the construction of compact large array in the near future. Such planar circuit technologies also hold promise for further improvement of the receiver capabilities by incorporating more circuit components on-chip to perform advanced functionalities such as side-band separating or LO noise rejection etc [20].

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