

Preface

This thesis describes the works completed in the duration of my doctorate study at the Department of Physics (Astrophysics) of the University of Oxford for the fulfilment of the D.Phil. degree requirements. Following from the general discussions about the millimetre and the sub-millimetre astronomy in Chap. 1, I describe a new type of feed horn in Chap. 2 that has high performance similar to the conventional corrugated horn, and yet is much easier to fabricate. This is followed by several chapters focusing on SIS mixers, starting with Chap. 3 which describes the fundamentals of SIS mixer theory and the experimental techniques used to assess the performance of the newly designed mixers. Chapter 4 presents the details of new SIS mixer designs, which is a central theme in this thesis, while Chap. 5 reports the measured performance of these mixers together with performance analysis. Chapter 6 describes the design and measured performances of the single-chip balanced SIS mixers at 700 GHz integrated onto an SOI (Silicon-on-Insulator) substrate, and Chap. 7 describes the design of integrated single sideband mixers such as sideband separating and balanced with sideband separating SIS mixers. In Chap. 8, I present two interesting features of the SIS mixers, namely the effect of heating in SIS tunnel junctions by the tunnelling currents, and the effect of Josephson currents on the sensitivity of SIS mixers near 700 GHz. In Chap. 9, I discuss an alternative method of generating LO power using infrared lasers, and finally in Chap. 10, I present our work on astronomical observations of $^{12}\text{CO } J=3\rightarrow 2$ emission line from two nearby galaxies, NGC 2976 and NGC 3351.

After the completion of the thesis, I have continued some of the work presented in this thesis and run several more experiments and analysis. Hence, several chapters in the current version of the thesis have been updated to reflect the progress of the subjects. The main body of the thesis however remains largely similar to the version submitted to the University of Oxford for the D.Phil. degree, except for these additional materials. It is therefore no longer fully compliant to the length requirement of the University.

During this post-doctoral period, I have also been engaged in several other new topics such as the development of high frequency supra-THz mixers, the construction of superconducting phase switches and the development of multi-pixel SIS mixer arrays. Therefore, I would like to take this opportunity to update the reader with some recent developments, especially in the area of millimetre and sub-millimetre detector technologies.

Recent Developments

Since the submission of the thesis, the field of millimetre and sub-millimetre astronomical instrumentations has moved on considerably. Atacama Large Millimetre/sub-millimetre Array (ALMA) is now fully operational and is performing routine observations for the ALMA Early Science Cycle Two science cases. It has since then produced impressive results with unprecedented sensitivity, albeit with only four receiver bands fully deployed to its 34 (out of the planned 54) 12-m antennas and 9 (out of the planned 12) 7-m compact array antenna currently installed on the Chajnantor site. Further development works are still ongoing to install the remaining antennas, and to commission new receiver bands. There is strong interest within the ALMA scientific community to extend the capability of ALMA beyond 1 THz limit as well. Apart from the ALMA observatory, several other millimetre and sub-millimetre instruments have also entered their routine observation phase now, such as the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA) observatory, the Balloon-borne Large Aperture Sub-millimeter Telescope (BLAST) and the Atacama Pathfinder EXperiment (APEX). A new millimetre and sub-millimetre observatory, the Green Land Telescope (GLT), has also been undertaken by the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), the Smithsonian Astrophysical Observatory (SAO), the MIT Haystack Observatory and the National Radio Astronomy Observatory (NRAO), to perform state-of-the-art THz observation at the peak of the Greenland ice sheet, complementing the scientific capability of the ALMA array in the southern hemisphere.

Apart from the ground-based and airborne experiments, the Herschel Space Telescope has now completed its mission and produced vast amount of state-of-the-art data and results. The millimetre and sub-millimetre instrumentation community has recently been focusing their effort on constructing new space telescopes such as SPICA (Space Infra-Red Telescope for Cosmology and Astrophysics telescope) and the Millimetron. FIRSPEX (Far-Infrared Spectroscopic Explorer), a small satellite mission has also been proposed jointly by the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) to perform an unbiased all sky spectroscopic survey between 0.69–1.9 THz with high spectral resolution. It consists of four heterodyne detection bands, targeting at the key molecular and atomic transitions near the 1 THz frequency range, and will be stationed along the Low Earth Orbit (LEO) when launched in 2021.

The extensive works on the detection of B-polarisation mode of the Cosmic Microwave Background (CMB) by the BICEP2 (Background Imaging of Cosmic Extragalactic Polarization 2) and the Keck Array, along with the impressive observational results from the Planck satellite mission have drawn attention from the worldwide scientific community to push for even more sensitive experiments to be performed. Most of these B-mode CMB experiments, including the POLARBEAR experiment mounted on the Huan Tran Telescope (HTT) and SPIDER (a balloon-borne polarimeter), incorporate a number of Transition Edge Sensor (TES) bolometer array in the focal plane to achieve ultra-sensitive polarisation signal detection. In order to achieve the unprecedented sensitivity required to successfully detect the B-mode CMB, the TES community have since then been focusing their effort on improving the optical coupling efficiency and increasing the transition temperature of the TES, along with the even more compact bolometer array design. It is well known, however, that TES detectors require complicated SQUID (Superconducting QUantum Interference Device) readout and suffer from low saturation power. Therefore, in the past few years, the development of the Kinetic Inductance Detectors (KIDs) that needs only a very simple readout system based on the frequency multiplexing superconducting resonant circuits at microwave frequencies has begun to gain traction. It has been piloted on several currently planned CMB experiments such as BLAST-TNG (The Next Generation) and there are programmes initiated recently to investigate their suitability to be deployed on balloon-borne and space-based instruments.

Another exciting new development in the millimetre and sub-millimetre detector area recently is the fast growing interest in the development of parametric amplifiers as ultra low noise detectors, especially the travelling wave kinetic inductance based parametric amplifiers developed at the California Institute of Technology (CalTech). Theoretically, a superconducting parametric amplifier can be configured to only half a quantum of noise to the incoming signal via a technique called noise squeezing. These sub-quantum limited amplifiers can be configured, if developed successfully, to be used as the first stage low noise amplifier for high frequency heterodyne receivers and readout for quantum computing experiment, or potentially as the front end detectors of a radiometer at sub-millimetre wavelength.

For heterodyne receivers at high THz region (2–5 THz), considerable research efforts have been invested in enhancing the intermediate frequency (IF) bandwidth of the hot electron bolometers (HEBs). Recent results from several groups in the Europe and United States of America have shown encouraging improvements in the IF bandwidth performance of the HEB detectors, with the indication that HEB detectors with several GHz (3–4 GHz) of IF bandwidth is possible. Nevertheless, this is still much narrower compared to the IF bandwidth achievable by the SIS receivers. Although the performance of SIS mixers is superior below and near the superconducting gap of niobium (~ 680 GHz), there is still much room for improvement. Two major areas currently pursued in the SIS mixer community are the development of SIS mixers near and above 1 THz, and construction of multi-pixel SIS mixer array at 200–900 GHz regime.

Supra-THz SIS Mixer

The sub-millimetre wave spectrum is rich in spectral lines which hold the key to understanding the chemical and kinematical structure of the cold interstellar medium (ISM). Two of the most important calling lines in our own and external galaxies above 1 THz are the [CII] (158 μm) and [NII] (205 μm) fine-structure lines. High resolution observations of these lines in the frequency range 1.0–1.5 THz, corresponding to the intermediate redshift range $0.5 < z < 1$ (approximately 6–9 Gyr after the Big Bang), will reveal vital information about the way in which galaxies form and evolve. This part of the THz spectrum is also rich in high- J transitions of the carbon monoxide (CO) ladder, that could provide valuable information about the temperature, density and other properties of interstellar gas. Combining these observations with the low- J transitions at sub-THz regime will allow the astronomers to probe the dust opacity of the surrounding ISM.

Many of the sub-millimetre observatories discussed earlier will be suited for observations above 1 THz, as they generally have superior main reflector specifications with surface profile sufficient for supra-THz operation and are either sited at high and dry environment or are stationed above the Earth's atmosphere. For example, the CO N+ Deuterium Observations Receiver (CONDOR) on the APEX 12 m telescope at the ALMA site in Chile with an elevation of 5050 m, was design to perform observations at these supra-THz frequencies. Even higher at 5525 m elevation on Sairecabur, the Smithsonian 80 cm Receiver Lab Telescope (RLT) has receivers for frequencies up to 1.5 THz, and the planned 25 m Cerro Chajnantor Atacama Telescope (CCAT) telescope at 5600 m on Cerro Chajnantor should have the dish that is able to operate at these frequencies as well.

Apart from the large single-dish telescope, ALMA as an interferometer can also be configured to operate above 1 THz. A new receiver cartridge covering the frequency range from 1.0–1.6 THz for ALMA, known as Band 11, has been proposed and has generated considerable interest from the sub-millimetre astronomy community. Interferometry with ALMA offers two distinct advantages over single-dish telescopes: First, even ALMA's most compact configuration would yield a resolution better than 0.4 arcsec at 1.3 THz; second, interferometric observations allow deep integration to faint flux levels even in the presence of atmospheric fluctuations. The combination of a wide-field THz focal-plane array on large single-dish telescope, and a narrow-field high-angular resolution THz receiver system on ALMA would therefore create a powerful observing capability.

The technological development for constructing a supra-THz receiver, however, is challenging. The key receiver components needed are high-gap SIS tunnel junctions, complete low-noise SIS mixer chips with low-loss transmission line, high performance feed horns and THz local oscillator (LO) sources. Nevertheless, the prospects are realistic as a consequence of some recent technical advances in new superconducting materials for SIS junction fabrication, such as niobium titanium nitride (NbTiN) and niobium nitride (NbN), and great improvements in mechanical and lithographic micro-machining techniques.

One of the main challenge in this aspect is to fabricate high quality SIS tunnel junctions using a high-gap superconductor. The quantum-limited performance of SIS mixers is restricted to frequencies below the superconducting energy gap of the superconductor. For niobium (Nb), the material used routinely for most of SIS receivers to date, this restriction implies an effective upper frequency limit of about 0.68 THz. Above this frequency, the superconductor starts to become lossy due to the breaking of Cooper pairs and the RF loss in the superconducting planar transmission lines increases substantially. This results in a rapid rise in the mixer noise temperature. Therefore, to operate at frequencies in the supra-THz region, higher gap superconductors are needed. Two of the most studied materials are the niobium titanium nitride and niobium nitride which have gap energies of about 5.0 mV and 5.8 mV (~ 1.2 THz and ~ 1.4 THz), respectively. The development of these materials for use as SIS mixers, although progressing, is very challenging and critical fabrication steps still need to be overcome. For example, it is difficult to fabricate high current density NbN junctions. However, complex thin film deposition processes associated with the fabrication of high-gap SIS devices are becoming better understood and are more effectively controlled now, and therefore show considerable promise for use as supra-THz detectors. The use of a combination of superconducting materials to alleviate the fabrication difficulties has shown to be a promising step towards pushing the SIS technology into the supra-THz region, but much more work is needed to explore this option.

Receiver performance does not, however, depend solely on the tunnel junction. For instance, a substantial improvement in sensitivity can be obtained by employing on-chip balanced and single-sideband mixers, which reduce noise from the LO and atmosphere respectively, and promote system stability. In addition, above 1 THz the noise contribution from waveguide and optical losses increases due to the skin effect. Care must be taken with regard to the design of the mixer embedding structure, including the coupling antenna, or feed horn, and beam-forming optics. Nevertheless, development techniques are improving and the use of high-precision electron-beam lithography in the fabrication of the SIS mixer circuits, state-of-the-art mechanical fabrication facilities, and most importantly the fabrication of planar transmission lines from low-loss superconducting materials, could provide enhanced performance. For example, fabricating thin-film transmission lines from NbN whilst maintaining the use of Nb tunnel junctions has shown to produce a substantial improvement in mixer noise temperature. Above 1 THz, it also becomes more pressing to have sufficient LO power. Hence it is critical that appropriate LO technology is available. An SIS mixer cannot operate without an LO source, and it is desirable that close integration of the LO source with the mixer is undertaken in order to minimise LO signal-power loss, maximise LO tuning range and ensure good overall system stability.

Sub-Millimetre Heterodyne Focal-Plane Array Receivers

Although ALMA has a near quantum-limited sensitivity with the use of niobium-based SIS mixer as front-end detector, a heterodyne focal-plane array with significant number of elements will undoubtedly increase ALMA's current mapping speed at these frequencies. For example, replacing the current single-pixel Band 9 or 10 receiver with a 2×2 compact mixer array will immediately quadruple the output of Band 9 and 10 science. The deployment of tens or even hundreds of pixel on to a compact focal-plane array will certainly be beneficial to large single-dish telescope such as APEX and the upcoming CCAT as well. This would provide the ability to map large scale structures and deliver the essential survey science needed in the era of ALMA, and induce a transformational change in the sub-millimetre astronomy similar to the revolution experienced in the infrared and radio astronomy many years ago. Considerable research efforts have therefore been invested in the recent years aiming at developing the underpinning technologies that would enable the construction of such high frequency large format focal-plane array.

There are a variety of technical challenges that are unique to heterodyne multi-pixel systems. In a generic single-pixel heterodyne receiver, the RF signal and the LO power are fed to the mixer chip through the cryostat window via the mixer feed horn and the Intermediate Frequency (IF) signal is extracted from the output of a high performance cryogenics amplifier following the mixer. In principle, a heterodyne array is an N channel of these signal chains packed in a tight configuration, but a practical array receiver will need to have an easy-to-fabricate large array of high performance feeds and mixer block with wide RF bandwidth, reproducible, easy to fabricate and easy to mount mixer chip, simple mechanism for suppression of Josephson tunnelling in a large number of detector chips, and a compact LO injection scheme that would fully harness all the available LO power.

There exist a variety of methods pursued by different groups in the community to address these challenges. One such scheme proposed based on the works here at the University of Oxford is to utilise the highly array-able multiple flare-angle smooth-walled horn and planar on-chip circuit integration technology to construct such focal-plane array. As shown in this thesis, the multiple flare-angle smooth-walled horn's performance is similar to that of a corrugated horn and yet much easier and cheaper to fabricate. They can be fabricated rapidly by milling directly into a block of aluminium plate using a profiled-tool. Utilising these horns will reduce significantly the cost and time required to construct a heterodyne array.

The back-to-back planar on-chip balanced SIS mixer architecture presented in this thesis will also be highly viable for construction of such medium/large format array. These balanced mixers were fabricated on a $15\ \mu\text{m}$ SOI substrate with fully integrated circuits fabricated on-chip using minimum photo-lithography steps. The mixer chip is so light that it can be supported by gold beam leads, avoiding the need of dicing and bonding with thin wires when the chip is mounted in the waveguide, thus simplifying the handling process significantly. Since all the required

superconducting circuits are integrated on-chip, it only requires a very simple mixer block structure, which is crucial for making large format SIS mixer arrays feasible.

The major advantage of a back-to-back balanced SIS mixer over single-ended mixer is its ability to improve the instrument stability, reject the LO sideband noise and make full use of the available LO power. This is especially important for high frequency mixers where the available LO power is often limited, and the need to feed an array of mixers with a minimal number of LO sources. The back-to-back architecture allows the RF and LO signal to be injected into the mixer chip from either side of the mixer chip, eliminating the use of a beam splitter. This further reduces the losses in the RF path, simplifies the RF/LO feeding mechanism, hence reduces significantly the physical size of the array and ensures a compact mixer array design.

Final Remarks

The work presented in this thesis describes the design and fabrication of various components required for constructing a heterodyne SIS mixers at the high sub-millimetre frequency range. These precursor works would hopefully pave the way to develop high density compact SIS mixer array and extend their applications above 1 THz. These high frequency SIS mixers, both single- and double-ended mixer chip designs, were fabricated using the recently developed silicon-on-insulator technology with beam lead electrodes. This SOI technology uses an inverted-etch process, resulting in very thin, as thin as 5 μm silicon substrates, simplifies the waveguide embedding structure and the mechanical arrangement. We believe that the SOI technology will be crucial to supra-THz mixer development, as all the mixer circuit components required can be fabricated onto a single mixer chip, avoiding the use of complicated mechanical machining. This does not only reduce the size of the mixer block and ancillary mechanical components needed to construct a complete heterodyne receiver, but it also relaxes the tolerance requirement on the machining blocks, which become critically difficult above 1 THz. The design and fabrication of a novel smooth-walled horn above 1 THz has also been demonstrated successfully, and recently, they have been employed to construct focal-plane array for many heterodyne and bolometric receivers even up to 1.5 THz. This and the single-chip SIS mixer technology will ensure repeatability in producing high quality heterodyne system, and promote their operations in the supra-THz frequency regime.

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