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Development of large terahertz heterodyne receiver arrays for future space observations

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Development of large terahertz heterodyne receiver arrays for future space observations

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Chapter 1

Introduction

This chapter gives an introduction into terahertz astronomy to state the scientific motivation of this thesis in Section 1.1. An overview of heterodyne detection techniques and an introduction to Hot Electron Bolometer (HEB) based heterodyne receivers are given in Section 1.2. Section 1.3 gives an introduction to heterodyne array receivers, and Section 1.4 outlines the structure of this thesis.

1.1 Terahertz astronomy

Terahertz (THz) radiation, which refers to electromagnetic waves within the frequency range between $0.3\text{--}10\times 10^{12}$ Hz ($1000\text{--}30\text{ }\mu\text{m}$), provides abundant information related to the birth and death of stars in galaxies. The THz radiation of our interest is mostly emitted by the interstellar medium (ISM), referring to the gas ($\sim 99\%$ in mass) and dust grains ($\sim 1\%$ in mass) between the stars. The interstellar gas in the Milky Way contains 90.8% (70.4% by mass) of hydrogen, 9.1% (28.1%) of helium, and 0.12% (1.5%) of atoms heavier than hydrogen or helium [1], and can be classified into 5 different phases each with a different density and temperature. The hot ionized medium (HIM), with the lowest density ($n \approx 0.004\text{ cm}^{-3}$) and the highest temperature ($T \geq 10^{5.5}\text{ K}$), accounts for more than 50% of the volume of the ISM. The warm neutral medium (WNM) accounts for $\sim 40\%$ of the volume of the ISM with $n \approx 0.5\text{ cm}^{-3}$ and $T \approx 10^{3.7}\text{ K}$. After being (photo)ionized by starlight and cosmic rays, the WNM becomes warm ionized medium (WIM), which accounts for $\sim 10\%$ of the volume of the ISM. Cold neutral medium (CNM) with $n \approx 30\text{ cm}^{-3}$ and $T \approx 10^2\text{ K}$ and cold dense molecular clouds (CDM) with $n \approx 10^3 - 10^6\text{ cm}^{-3}$ and $T \approx 10 - 50\text{ K}$ account for $\sim 1\%$ and $\sim 0.01\%$ of the volume of the ISM, respectively [2-4]. THz radiation is emitted mostly by relatively cold ($\sim 30\text{ K}$) atomic and molecular phases.

As illustrated in Figure 1.1, the life cycle of the ISM can be divided into six stages, each of which contains different phases of the gas. The WNM and WIM phases dominate the earliest stages of star formation (top panel of Figure 1.1). These phases are best traced by atomic and ionic fine structure lines. The energy shell of an atom is divided into subshells based on the interaction between the electron orbital angular momentum and the spin angular momentum, and transitions between these subshells are the source of fine-structure lines [2]. Due to the low critical densities, referring to the density below which each collision leads to a photon being emitted and above which collisional processes dominate over radiative processes [2], of ionized nitrogen fine structure line [NII] (a few tens of electrons per cm^3), it can trace the low density WIM in this stage. As the temperature of the gas decreases, the WNM and WIM are converted to CNM HI (atomic hydrogen) clouds, and the thermal energy is radiated away by the emission of the ionized carbon fine structure line ([CII]). With the continuing drop of their temperature, the clouds become denser. To a certain stage, they become so dense that their gravity overwhelms their thermal pressure and the clouds collapse. Owing to the high density of the clouds, the hydrogen atoms and the dust grain in their outer layer prevent the far ultraviolet (FUV) light ($h\nu = 6 - 13.6\text{ eV}$) from going into the clouds' interior. Therefore the inner part of the clouds forms H_2 (molecular hydrogen) clouds. During this

process, molecular clouds form and radiate emission lines such as CO. Combine atomic carbon[C I] fine structure lines, CO molecular lines, and the [C II] line, one can trace the C/CO transition process.

Figure 1.1. Life cycle of the interstellar medium. It can be divided into six phases. During this life cycle, ionized/atomic fine structure lines and molecular lines are emitted and act as tracers to enable us to understand the life cycle of ISM. [2].

As the temperature of the clouds decreases, the movements of the particles slow down and the volume becomes smaller, leading to an increase in density, which causes the clouds to further shrink and then break into clumps. After the density of the contracting clouds becomes higher than 10^5 cm^{-3} , infrared emission from dust is also an efficient way to radiate away the thermal energy of the clouds. The process continues until the clouds are dense enough and the optical depth of the clouds thick enough that the thermal energy stops being radiated away. Then the clouds begin to heat up and the thermal energy and the gravitational energy reach an equivalence. Now the clouds are called protostar, which is the earliest stage in the process of stellar evolution. In the process of star formation, a disk forms, which allows the young protostar to accrete materials and mass from its parent cloud, and these materials and mass are needed for the young protostar to become a main sequence star. The thermal energy, the gravitational energy as well as the rotational angular momentum of the star continue to increase. In order to transfer the angular momentum back to the ISM, a bipolar outflow extended from each pole forms. Later, the outflow will disappear with the subsidence of accretion. As the accretion disk cools down, it will turn into a

protoplanetary disk. In this phase the atomic oxygen fine structure line [OI] (4.745 THz) is brighter than the [CII] line since it has a higher critical density [3]. When nuclear fusion starts in the stellar interior, high-mass stars continue to emit FUV and extreme ultraviolet (EUV) photons, and lower mass stars continue to drive winds into the ISM. Owing to nuclear fusion, the ISM materials are enriched with heavy elements. At the end of the stellar evolution, high-mass stars become supernova and low-mass stars lose up to half their mass in their winds. Most of their mass will be fed back into the ISM. After this stage, the clouds disrupt into WNM and WIM components, backing to the earlier stage as we described in the beginning.

As we can see from Figure 1.1, the [CII] line appears in almost every stage of the life cycle. Therefore, it is the most important line for tracking the life cycle of the ISM. Table 1 lists the properties of the most important ionized/atomic fine structure lines and the molecular lines with emission in the 1-10 THz region. The upper level energy refers to the energy of the emitting level of each line, expressed in K by dividing by the Boltzmann constant $k_B=1.38\times10^{-23} \text{ J}\cdot\text{K}^{-1}$. Tracing these lines enables us to track the life cycle of the ISM, understanding of which helps us answer the unsolved questions: the origin and formation process of interstellar clouds, the condition and rate of star formation, the way stars return enriched materials to the galaxy, and the evolution of galaxies.

Table 1.1. Ionized/atomic fine structure lines and molecular lines[2,5,6]

Species	Frequency (THz)	Wavelength (μm)	Upper level energy (K)	Critical density (cm^{-3})
CII	1.901	157.7	91	2.3×10^3
NII	2.459 / 1.461	121.9 / 205.2	188 / 70	310 / 48
OI	4.745 / 2.060	63.2 / 145.5	228 / 329	4.7×10^5 / 9.4×10^4
^{12}CO ($J=13\rightarrow12$)	1.497	200.2	503	2.5×10^6
^{12}CO ($J=11\rightarrow10$)	1.267	236.6	365	1.4×10^6
^{12}CO ($J=9\rightarrow8$)	1.037	289.1	249	8.4×10^5
HD ($J=1\rightarrow0$)	2.675	112.1	128	10^6

1.2 Terahertz heterodyne detection

Heterodyne detectors consisting of a mixing element, a local oscillator (LO), a low noise amplifier at the gigahertz (GHz) intermediate frequency, and a spectrometer; combine a light intensity measurement with an exceptionally high spectral resolution. The high spectral resolution $R=f/\Delta f \sim 10^6$ and corresponding velocity resolution $\Delta v = 300$ m/s of the heterodyne detection allows us to disentangle closely spaced lines at different frequencies and to measure line profiles. The latter tells us about the dynamics of the observed gas clouds.

The process of heterodyne detection is the transformation of one piece of THz spectrum that contains the celestial information to a lower frequency, i.e. tens of GHz, so it can be amplified and processed. In this process, the THz radiation and a strong signal from the LO are combined with a set of optics and coupled into a mixer, which transfers the THz radiation ω_{s1} and ω_{s2} to a lower sideband (LSB) intermediate frequency (IF) $\omega_{IF} = |\omega_{s1} - \omega_{LO}|$ and an upper sideband (USB) IF $\omega_{IF} = |\omega_{s2} - \omega_{LO}|$, as shown in Figure 1.2 (b). The IF signal conserves the spectral and phase information of the celestial signal, and is amplified by a low-noise amplifier and processed by a spectrometer. Mixers that are designed to separate the two sidebands into two IF outputs are called single sideband (SSB) mixers, while mixers containing two sidebands in one IF output are called double sideband (DSB) mixers. The latter type is most common in the THz region owing to its simplicity [2].

Figure 1.2. The process of heterodyne detection. (a) The local oscillator (LO) signal and the celestial signal are combined by an optical combiner such as a mylar beam splitter and are coupled into the mixer. After the signal is down converted in the mixer, it is amplified by a low-noise amplifier (LNA) or an LNA chain, and then recorded by a spectrometer. (b) The down converted frequency, which is also called intermediate frequency (IF). The IF signal conserves the spectral information of the celestial signal.

1.2.1 THz Mixer types

The mixing element is essential because it converts the THz frequency to an IF. There are three types of THz mixers known to the radio astronomy community: Schottky (diode) mixers, superconducting-insulator-superconductor (SIS) mixers, and hot electron bolometer (HEB) mixers. Figure 1.3 shows microscope images of these three types of mixers.

Figure 1.3. Microscope images of (a) a Schottky mixer, (b) an SIS mixer, and (c) an HEB mixer.

A Schottky mixer is based on a semiconductor-metal non-linear device. Compared to the other two mixers, an advantage is that it does not require a cryogenic environment, which is often one of the factors that limit the lifetime of space telescopes. Besides, Schottky mixers are stable and can be used over a wide frequency range (up to several THz), and have the widest gain bandwidth (>50 GHz) among the three types of mixers [7]. However, Schottky mixers require high LO power (≥ 1 mW) and have the highest noise temperature among all the mixers, reaching 1800 K at 500 GHz [8] and 70000 K at 4.75 THz [9]. Their noise decreases if Schottky mixers work at a cryogenic temperature, e.g., the noise at 500 GHz decreases to 1200 K if the mixer is cooled down to 20 K. A Schottky mixer has been used in early far-infrared telescopes, such as the airborne-based Kuiper Airborne Observatory [9,10], which operated from the years 1974 to 1995.

An SIS mixer is a device using the nonlinear current-voltage characteristics of a superconducting junction to achieve low-noise mixing. Therefore, it requires a cryogenic temperature. It has a relatively wide IF bandwidth, reaching 20 GHz, and the lowest noise temperature among the three types of mixers. The lowest DSB receiver noise temperature of an SIS mixer is ~ 85 K at 500 GHz [8] and 500 K at 1 THz [11]. Besides, it requires much less LO power ($1\text{--}3\ \mu\text{W}$) than Schottky mixers. Owing to its advantages mentioned above, SIS mixers are the most popular mixing devices at the frequency range between 0.3–1.1 THz, e.g. for ALMA [12]. However, the energy gap of their superconducting materials limits the working frequency of the SIS mixers, and they become less sensitive or not working at frequencies above 1.1 THz.

An HEB mixer uses the bolometric effect of the superconducting to normal transition of a superconducting bridge to achieve low-noise mixing. Thus it also requires to be operated in a cryogenic environment. Compared to the SIS mixer, it operates at a wider frequency range (0.3–6 THz), which is very useful because many emission lines lie also at frequencies > 1.1 THz, e.g., [CII], [NII], and [OI]. HEB mixers are based on an ultra-thin superconducting film (several nanometers) such as niobium nitride (NbN) or niobium titanium nitride (NbTiN) with a T_c of 8–10 K. The HEB mixers based on NbN have shown an IF bandwidth of 3–4 GHz [13], which are determined by the electron-phonon interaction time in NbN and the phonon escaping time from the NbN to the substrate. Figure 1.4 (a) summarizes the measured noise temperature of HEB mixers from different groups in the world, from 300 K at 1.3 THz [14] to 1150 K at 5.25 THz [15]. HEB mixers have a relatively narrow IF gain bandwidth and are sensitive to fluctuations of LO amplitude and FIR background, which make the performance of an HEB less stable. Because of this, the amplitude of the LO needs to be stabilized [16]. They have a relatively low noise temperature and require the lowest level of LO power (~ 200 nW). The latter is an advantage when HEB mixers are used in a large array because the power of existing LO sources is limited. Based on these and the ability to be operated at higher frequencies, the HEB mixer is the choice of heterodyne detectors to observe emission at THz frequencies from the Milky Way and other nearby galaxies. NbN HEB mixers have been used in some telescopes, for instance, Band 6–7 of the Heterodyne Instrument for the Far-Infrared (HIFI) on board of Herschel Space Observatory [17].

HEBs based on a new superconducting material, Magnesium diboride (MgB_2), have been developed in the last decade. They have the advantage of operating at a higher ambient temperature, e.g., 20 K and a larger IF bandwidth (11 GHz)

compared to NbN HEBs. The noise temperature of a MgB_2 HEB is 930K at 1.63 THz [18] and 2920 K at 5.3 THz (with a working temperature of 20 K). The latter was demonstrated in this thesis. Due to the higher critical temperature of MgB_2 , such an HEB needs more LO power ($\sim 10 \mu\text{W}$) than NbN HEB, which is two orders of magnitude less than the LO power required for Schottky mixers. Figure 1.4 (b) summarizes the measured noise temperature of MgB_2 HEB mixers from three groups in the world.

Figure 1.4. (a) DSB receiver noise temperatures of NbN HEB mixers reported at frequencies from 0.6-6 THz, reported by different groups in the world. (from J. R. Gao, up to 2021). (b) Noise temperatures of MgB_2 HEB mixers measured at frequencies from 0.6-6 THz, reported by different groups in the world (up to 2021).

1.2.2 Hot electron bolometer and local oscillator

A hot electron bolometer is a sensor that measures the power of incident radiation through the resistance change in a temperature-dependent resistor, fabricated on a superconducting thin film. Figure 1.5 shows a schematic resistance-temperature curve for a superconducting thin film bridge. To make the HEB mixer work in the sensitive region, one needs to bias the HEB mixer to the transition state, which gives a large response on the resistance with a small change of temperature. This is achieved by a combination of DC power and LO power.

Figure 1.5. Resistance-temperature curve for a superconducting thin film bridge.

One uses an antenna to effectively couple the RF radiation (to be measured) and the LO signal to the superconducting bridge. As illustrated in Figure 1.6, there are two optical schemes to couple the RF radiation to an HEB mixer: waveguide coupling and quasi-optical coupling. Waveguide coupling uses a feed-horn antenna to couple the radiation from free space to a waveguide mounted with an HEB [19,20]. For the quasi-optical coupling, a lithographic planar antenna is integrated with an HEB on a chip. Commonly used lithographic antennas include broadband double-slot and spiral antennas [21] due to their performance and easy manufacturing. The incoming radiation is coupled into the chip that is attached to the back side of an elliptical lens or a hyper-hemispherical lens, both of which have the same material as the substrate of the HEB.

Figure 1.6. Waveguide coupled HEB and quasi-optical coupled HEB. (a) (b) Assembled waveguide HEB mixer block and 3D CAD model of the feedhorn clamp [22]. (c) Optical microscope image of a

waveguide coupled HEB mixer [22]. (d) Assembled lens antenna coupled HEB mixer [23]. (e) SEM micrograph of a twin slot antenna coupled HEB mixer [24]. (f) SEM micrograph of a spiral antenna coupled HEB mixer.

To pump an HEB mixer to the transition region, it requires sufficient LO power to break the Cooper-pairs and elevate the quasi-particles (or electrons) to a temperature around T_c . Solid-state THz sources include photodiodes [25], resonant tunneling diodes [26], heterostructure barrier varactors [27], and Schottky diode-based frequency multipliers. Among them, Schottky diode-based frequency multipliers are widely used at ground, airborne, and space-based millimeter /submillimeter-wave observatories. The frequency multipliers have the advantage of being able to work at room temperature, a tunable fractional bandwidth of 15%-20%, and a relative low DC power dissipation [9]. However, with increasing frequency, the output power of the frequency multipliers decreases rapidly, from 1 mW at 1.6 THz [28] and 60 μ W at 1.9 THz [29] to 18 μ W at 2.58 THz [30]. They can produce signals at frequencies up to 2.7 THz until now [31].

Beyond 1.2 THz, quantum cascade lasers (QCLs) can provide high output power. Thus they are used as LO for single HEB mixers, but also are the workhorse for an HEB mixer array. Current THz QCLs have been demonstrated to cover the frequency range from 1.2 THz to 5.0 THz, and their output powers reach more than 200 mW in continuous-wave mode (relevant to LO applications) and watt level in pulsed mode [32-35]. THz QCLs work typically at a cryogenic temperature (10-77 K) [36], but QCLs with a higher operating temperature have also been studied, for instance, THz QCLs (at $\sim$ 4 THz) with a maximum operating temperature of 250 K were reported in [37].

1.3 Heterodyne receiver arrays and their challenges

Heterodyne receiver arrays, compared to a single pixel receiver, are capable of mapping the same area of sky in less observation time, which not only saves the time of an observatory, but also provides higher image fidelity. Heterodyne array receivers based on superconducting SIS mixers and HEB mixers are used in ground-based and airborne telescopes. An SIS mixer array, due to its high sensitivity, relative large bandwidth, and low requirement on the local oscillator (LO) power, is widely used in ground-based telescopes, including the Caltech Submillimeter Observatory[38], Atacama Pathfinder EXperiment (APEX) [39], IRAM 30 m telescope [40], KOSMA 3 m telescope [41], the NANTEN2 telescope [42], James Clerk Maxwell Telescope [43], Heinrich Hertz Telescope [44].

Due to atmospheric absorption (mainly by water vapor) of THz radiation beyond 1 THz, the receivers ideally need to be operated from space to avoid signal loss. The limited cooling power, volume, and mass of a space telescope limit its lifetime. Thus, mapping more area during the limited lifetime is highly demanded. The Stratospheric Terahertz Observatory (STO) was the first attempt with a 2×2 pixel receiver array, which flew on a balloon for 14 days in 2012 [45] although the mixer array was not in operation. Its successor STO2, which has 2 pixels at 1.4 THz, 2 pixels at 1.9 THz, and 1 pixel at 4.7 THz, flew in December 2016 for 22 days [46]. In 2022, their successor, GUSTO, will be launched from Antarctica, which aims to fly for 70 days in the stratosphere (above 40 km) with 2×4 pixel receivers at frequencies of 1.4, 1.9, 4.7 THz [47]. The Stratospheric Observatory for Infrared Astronomy (SOFIA), an airborne telescope, is equipped with the upGREAT array receivers consisting of 2×7 pixel array for 1.9-2.5 THz and a 1×7 -pixel array for 4.7 THz [48]. There are also some heterodyne array receivers that are proposed or planned. For the space-based mission, HERO for the Origins Space Telescope (OST) is proposed to have two bands with 4×4 -pixel SIS mixer array and four bands with 8×8 -pixel HEB mixer array [49].

A heterodyne array consists of multi-pixel mixers, a multi-beam LO, and the same number of IF chains and back-ends as the pixels. Additionally, there is a need for an optics system, which is designed to match the beams of the mixer array to the telescope. To effectively couple the LO to the array of mixers, all the beams of the array LO should be as Gaussian shaped as possible and their power should be uniformly distributed. The former is important to couple each beam effectively to each HEB, while the latter is essential for ensuring a uniform sensitivity of the mixers in the array. Therefore, additional optical components are needed to shape the LO beam into a Gaussian beam and to multiplex the LO beam. A feedhorn array or lens array is needed to effectively couple the celestial signal and the LO signal to the HEB. Considering the feasibility in fabrication, a lens array is more favorable. After transferring to the intermediate frequency, the following low-noise IF amplifiers need to be operated at cryogenic temperatures, so it is crucial to reduce the power dissipation of the amplifiers. It is also worth mentioning that the configuration of having an individual spectroscopic back-ends for each receiver leads to a significant complexity, weight, and mass for the system, especially for large arrays (>100 pixels).

1.4 Structure of the thesis

This thesis focuses on developing some key technologies for a large heterodyne array receiver using HEB mixers for the next generation of far-infrared space missions, which concern the following aspects:

- 1) A beam filter to shape the emitted beam of a QCL to a Gaussian beam with a good efficiency;
- 2) A Fourier grating as a beam multiplexer to generate multiple beams from a single QCL with a high efficiency and a good uniformity;
- 3) HEB mixers using a novel superconducting MgB_2 film to offer low noise, a larger IF bandwidth and the ability to be operated at a higher bath temperature than 4 K.
- 4) Concept study of an unprecedented large heterodyne array of 1000-pixel mixers based on NbN HEBs and a quantum cascade laser

The thesis is organized as follows. Chapter 2 introduces the background theory of a THz QCL, a back-to-back lens system, a Fourier grating, and an HEB mixer. Chapter 3 presents the design, simulation, and measurement of a back-to-back lens system, which can effectively shape the QCL beam to a Gaussian beam. Chapter 4 describes the design, simulation, measurement and analysis of an 81-pixel Fourier grating, which divides a QCL beam to 81 sub-beams with a high efficiency and fair uniformity. Chapter 5 illustrates simulations on the bandwidth of a 8-pixel asymmetric Fourier grating, designed for the 4.7 THz band for the GUSTO telescope. Chapters 6 & 7 present the characterization of the receiver noise temperature and the IF bandwidth of MgB_2 HEB mixers at 1.6 THz, 2.5 THz, and 5.3 THz. Chapter 8 summarizes the state of the art of the technologies needed for a very large heterodyne array and describes a concept and design study of a 1000-pixel heterodyne array receiver based on lens-antenna coupled HEB mixers. Chapter 9 is a summary of the entire thesis.

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Chapter 2

Background theory of a heterodyne receiver

As illustrated in Chapter 1, a heterodyne array receiver consists of an LO, the optics to shape and multiplex the LO beam, mixers, low noise amplifier chains, and spectrometers. Since this thesis focuses on LO, optics, and mixers, this chapter gives some background information about the QCL used in this thesis, the optical component to filter the QCL beam to a fundamental Gaussian beam, the optical component to multiplex the QCL beam, and the physics and performance of an HEB mixer. Section 2.1 introduces the LO used in this thesis, which is an unidirectional third-order distributed feedback THz QCL, providing a 3.86 THz emission and a 10-20 mW output power. The high output power enables us to study the performance of the optical components. Section 2.2 gives the mathematical background for the optical components, including a back-to-back lens system used to shape the QCL beam into a fundamental Gaussian beam and a Fourier phase grating used to divide one QCL beam into multiple beams. This information helps to understand the design of the optical components depicted in Chapter 3 and Chapter 4. Section 2.3 describes the physics and main performance parameters of an HEB mixer, including its conversion gain, noise temperature, and IF bandwidth. The techniques for measuring an HEB mixer are also included. Knowing this background, we can better understand the contents of Chapters 6 and 7.

2.1 Unidirectional third-order distributed feedback THz QCL

Unlike traditional semiconductor lasers, the emitted radiation of which is restricted to frequencies greater than the bandgap energy of the semiconductor material, quantum cascade lasers (QCLs) make use of the intersubband transitions in a semiconductor structure to achieve a wide frequency operation range [1]. As shown in Figure 2.1 (a), a QCL contains an electrically biased stack of quantum wells, which are the thin layers of a semiconductor medium embedded between other semiconductor layers with a wider band gap. The medium containing all the quantum well structures is called gain medium or active region. When an electron is injected into a quantum well, it transits from a high energy level to a low energy level and emits radiation whose energy equals the difference between the two energy levels. Then this electron will tunnel to the next quantum well and emit radiation via another transition. This process continues in all the periods of quantum wells and thus the intensity of the emitted laser is enhanced. The emitting frequency of the QCL is not determined by the material properties but by the designed parameters, especially the thickness of the quantum well. Such thin layers are grown by molecular beam epitaxy (MBE) or metal-organic vapor phase epitaxy (MOCVD) process, and the thickness of the layers can be down to a single atomic layer and accurately controlled [2]. Therefore, QCLs can be designed to operate in the THz region.

Figure 2.1. Simplified schematic of the active region of a QCL. The active region contains multiple quantum wells in series. An electron is injected into a quantum well, inside which the transition happens and radiation is emitted. After that, the electron

tunnels to the next quantum well and continues this process to enhance the intensity of the QCL.

In the THz region, the absorption of radiation by free carriers in the semiconductor is strong (it is proportional to the square of the wavelength). Therefore, waveguides must be designed to minimize overlap with doped regions. THz QCLs have been demonstrated to operate between 0.84-5.0 THz, and use two types of waveguide configuration: the semi-insulating surface-plasmon and the metal-metal waveguide [3]. The first THz QCL was demonstrated in 2002 using a semi-insulating surface-plasmon waveguide by Alessandro Tredicucci's group in Pisa. In 2003, a metal-metal waveguide QCL was demonstrated at 3.0 THz by Qing Hu's group at MIT [4]. Metal-metal waveguide QCLs tend to have higher operating temperatures, but the emitted radiation has divergent beam patterns and low output power owing to the subwavelength dimensions of the emitting aperture [5-7]. Many efforts have been made to improve the beam pattern and the output power of the metal-metal waveguide QCL. One method is to micromachine a mode-matching device to the exit facet of the QCL, such as a horn antenna [8], hollow waveguide [9,10], and silicon hyper-hemispherical lens [11,12]. The use of distributed-feedback (DFB) structures and two dimensional (2D) photonic crystal cavities (PCC) on the QCL have been studied and proved to achieve single mode operation with narrow beam patterns [13-19]. 2D PCC-based THz QCLs are not desirable for astronomical application due to their high power dissipation (> 20 W), which exceeds the limited power budget of a space telescope [20]. Third-order DFB QCLs, on the other hand, are most promising for LO applications. From Figure 2.2, the structure contains many periods, the length of which is carefully designed combining the modal effective index (n_{eff}) to let the radiation in both directions constructively interfere. Therefore, the output beam achieves single spot emission, enhanced intensity, and a low divergence. The Figure 2.2 (b) is an example of the output beam from a third-order DFB THz QCL [21].

Figure 2.2. (a) Schematic of the third-order DFB QCL [20]. (b) The output beam in intensity from a third-order DFB QCL [21].

Normally a 3rd order DFB QCL emits radiation in both directions, as shown in Figure 2.2. However, only the radiation from one direction is used, and the radiation from the opposite direction is wasted. Unlike conventional Fabry-

Perot laser devices, the unidirectional emission of which can be easily achieved by a high-reflectivity (HR) coating or distributed Bragg reflector attached to the rear facet [22], a 3rd order DFB THz QCL has a subwavelength cross-section and thus a large fraction of the laser radiation propagates outside the waveguide. Therefore, an HR coating or distributed Bragg reflector is unable to achieve unidirectional emission. For the QCL used in this thesis, a new scheme is used to make the radiation come out in only one direction. Figure 2.3 (a) is an optical micrograph of half of the laser chip, which contains 20 lasers, spanning from 3.85 THz to 3.87 THz. For each waveguide, reflectors are placed in certain places on the structure, and these reflectors make the forward radiation constructively interfere and the backward radiation destructively interfere. In this way, the output power of the QCL increases by a factor of nearly 2, reaching 10-20 mW output power at a temperature of 10-30 K.

Figure 2.3. (a) Optical microscope photo of half of the third-order DFB THz QCL. (b) SEM micrograph of one waveguide. (c) Simulated far-field radiation pattern (top) and the corresponding electric field distribution inside the laser (bottom) in arbitrary units (From Ali Khalatpour at MIT).

2.2 Optics for local oscillators

Both a waveguide coupled HEB device and a quasi-optical coupled HEB mixer usually have a Gaussian input beam. To effectively couple the LO power to the HEB mixer, it is required that the LO beam is Gaussian distributed or as close as possible to a Gaussian beam. However, the beam from the QCL deviates from a Gaussian beam to different extents. Additional optical components are needed to shape the QCL beam into a Gaussian beam. For this, we have introduced a so-called back-to-back beam filter. Besides, to build a heterodyne array receiver, an LO array is required. It is not realistic to use a QCL for each mixer owing to the high power consumption, complexity, and high cost. Thus additional optical components for dividing an LO beam into multiple beams are a key technology

to build heterodyne receiver arrays. For this, we will introduce a phase grating here. In this section, the physical background of the back-to-back lens system to shape an LO beam and the background of the Fourier phase grating to multiplex an LO beam are introduced.

2.2.1 Back-to-back lens system as a beam filter

The far field beam pattern of a waveguide coupled mixer and a lens-antenna coupled mixer is a nearly fundamental Gaussian beam [23-26]. Therefore, to maximally make use of LO power and reduce the stray light in the optical path, which is not coupled to the HEB, it is desirable to have a fundamental Gaussian beam pattern for the LO. Although the 3rd order DFB QCL structure reduces the beam divergence and improves the output power of the laser, its beam pattern still deviates from a fundamental Gaussian beam. In addition to mounting a horn antenna, a hollow waveguide, or hyper-hemispherical silicon lenses near the exit facet of the QCLs, a combination of a spherical lens and a diaphragm [27] and a back-to-back corrugated feedhorn pair [28,29] have also been demonstrated to shape the QCL beams. In order to shape the QCL beam to a Gaussian beam while reducing the power loss during this process, we designed a back-to-back silicon (Si) elliptical lens system in this thesis, which consists of two elliptical Si lenses mounted back-to-back (B2B) and an opening aperture defined on a thin gold layer between the lenses. Figure 2.4 (a) is a 3D model of the lens system and (b) shows the geometry of an elliptical lens. According to the geometry of an ellipse, the eccentricity e is equal to the ratio between the refractive index of air ($n_{air}=1$) and the refractive index of Si ($n_{Si}=3.42$) [30]. Therefore, the semi-minor axis of the ellipse a , the semi-major axis b , and the distance from the coordinate origin to the focus c have the following relations [31]:

$$e = \frac{\sqrt{b^2 - a^2}}{b} = \frac{1}{n_{Si}}, \quad (2.1)$$

$$b = \frac{a}{\sqrt{1 - \frac{1}{n_{Si}^2}}}, \quad (2.2)$$

$$c = \sqrt{b^2 - a^2}. \quad (2.3)$$

Figure 2.4. (a) 3D model of the back to back Si lens system. (b) Schematic of an elliptical lens. (c) Light propagation through a homogenous thin film.

The transmission for the air-silicon interface is $\sim 70\%$ [32], namely, for the B2B lens system with two air-silicon interfaces, $\sim 50\%$ power of the incident beam is reflected. Thus, anti-reflection (AR) layers are coated on the surface of the two Si lenses to reduce the power loss of the lens system. Figure 2.4 (b) depicts the propagation of a light through a homogenous film. According to the Fresnel formulae, the transmissivity T and reflectivity R through the AR layer can be expressed as [33]:

$$R = \frac{r_{12}^2 + r_{23}^2 + 2r_{12}r_{23}\cos 2\beta}{1 + r_{12}^2r_{23}^2 + 2r_{12}r_{23}\cos 2\beta}, \quad (2.4)$$

$$T = \frac{n_3 \cos \theta_3}{n_1 \cos \theta_1} \frac{t_{12}^2 t_{23}^2}{1 + r_{12}^2 r_{23}^2 + 2r_{12}r_{23}\cos 2\beta}, \quad (2.5)$$

where β is:

$$\beta = \frac{2\pi}{\lambda_0} n_2 h \cos \theta_2, \quad (2.6)$$

where, n_1 , n_2 , and n_3 are the refractive indexes of the mediums, λ_0 is the wavelength of the light in the air, and h is the thickness of the film. Parameters r_{12} and r_{23} are the reflection coefficients from medium 1 to medium 2 and from medium 2 to medium 3. Parameters t_{12} and t_{23} are the transmission coefficients from medium 1 to medium 2 and from medium 2 to medium 3. They can be calculated from the refractive index of the medium and the incidence and exit angles of the light (see Figure 2.4 (c)):

$$t_{12} = \frac{2n_1 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_2}, \quad (2.7)$$

$$t_{23} = \frac{2n_2 \cos \theta_2}{n_2 \cos \theta_2 + n_3 \cos \theta_3}, \quad (2.8)$$

$$r_{12} = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2}, \quad (2.9)$$

$$r_{23} = \frac{n_2 \cos \theta_2 - n_3 \cos \theta_3}{n_2 \cos \theta_2 + n_3 \cos \theta_3}. \quad (2.10)$$

When $\sin 2\beta = 0$, namely,

$$h = \frac{m\lambda_0}{4n_2 \cos \theta_2} \quad (m = 0, 1, 2, \dots), \quad (2.11)$$

the derivative of the reflectivity R with respect to the thickness of the film h

$$\frac{dR}{dH} = 0,$$

and the reflectivity reaches its maximum or minimum. When m is odd,

$$h = \frac{\lambda_0}{4n_2 \cos \theta_2}, \frac{3\lambda_0}{4n_2 \cos \theta_2}, \frac{5\lambda_0}{4n_2 \cos \theta_2} \dots \dots \quad (2.12)$$

For a normal incident case, the reflectivity of the film is calculated:

$$R = \left(\frac{n_1 n_3 - n_2^2}{n_1 n_3 + n_2^2} \right)^2. \quad (2.13)$$

From Eq. 2.12 and 2.13, the reflectivity R is zero when the refractive index of the AR coating $n_{AR} = \sqrt{n_{air} n_{Si}}$, and the thickness $h = \lambda_0 / 4n_{AR}$.

The opening aperture is defined on a thin gold layer between the lenses. Since gold is highly reflective for THz radiation, it prevents the undesired part of the incoming beam from going through the lens system. The skin depth of gold δ , defined as the depth at which the intensity of the radiation inside the gold falls to $1/e$ of the radiation intensity at the surface, can be calculated from [34]:

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \nu}}, \quad (2.14)$$

where $\rho = 2.44 \times 10^{-8} \Omega/m$ is the electrical resistivity of gold, $\mu_0 = 4\pi \times 10^{-7} H/m$ is the magnetic permeability constant of free space, and ν is the frequency of the radiation. The thickness of the gold layer is required to be larger than this skin depth to effectively block the undesired part of the incoming beam.

The detailed design, simulation, measurement, and analysis of the B2B lens system are described in Chapter 3.

2.2.2 Phase grating

A beam multiplexer, which is capable of dividing a single LO beam into multiple beams, is required for building a large heterodyne array receiver. To maximally make use of the LO power and distribute the power uniformly to each pixel, the multiplexer should have a high efficiency and good uniformity. A succession of beam splitters are used to achieve multiple beams in the HARP instrument on the James Clerk Maxwell Telescope (JCMT) [35]. Although they can achieve a relatively high efficiency and good uniformity, it imposes a high complexity and is difficult to align when applying to large LO arrays. A phase grating, or Fourier grating, is a single component, providing an elegant way to generate multiple beams. The high frequency band (4.7 THz) of SOFIA/GREAT uses a 7-pixel phase grating and the 4.7 THz band of GUSTO uses a 8-pixel phase grating to divide one single QCL beam into multiple beams [36,37]. A phase grating is a periodic structure that splits and diffracts light into multiple beams in different directions by manipulating the phase of the light. The working principle is based on diffraction theory.

Figure 2.5. Diffraction geometry (See text for symbols).

Figure 2.5 illustrates the diffraction geometry from one plane to another. Assuming the x_0y_0 plane is uniformly illuminated, the field distribution of which is $U_0=1$. There is an aperture Σ on the x_0y_0 plane, only the light inside which passes while the other light is blocked. The transmission function of the aperture is expressed by $t(x_0, y_0, 0)$. According to scalar diffraction theory, when the distance $z \gg k(x_0^2 + y_0^2)_{\max}/2$, where the angular wave number $k = 2\pi/\lambda$ and λ is the wavelength of the light, the xy plane enters the region of Fraunhofer

diffraction (far field) and the field distribution $U(x, y, z)$ can be expressed as [38]:

$$U(x, y, z) = \frac{e^{jkz} e^{j\frac{k}{2z}(x^2+y^2)}}{j\lambda z} \iint t(x_0, y_0, 0) \exp[-j2\pi(\frac{x}{\lambda z}x_0 + \frac{y}{\lambda z}y_0)] dx_0 dy_0. \quad (2.15)$$

From Eq. 2.15, the field distribution $U(x, y, z)$ in the far field is the Fourier transform of the transmission function $t(x_0, y_0, 0)$ of the aperture evaluated at the spatial frequencies $f_x = x/\lambda z$ and $f_y = y/\lambda z$. Therefore, the diffraction pattern of multiple beams can be achieved by properly designing the transmission function $t(x_0, y_0, 0)$. For a phase grating, the transmission function only contains the phase modulation part and can be written as:

$$t(x_0, y_0, 0) = \exp(i\Delta\phi(x_0, y_0)), \quad (2.16)$$

where $\Delta\phi(x_0, y_0)$ is the phase modulation function, which determines the far field diffraction pattern. To produce multiple beams, $\Delta\phi(x_0, y_0)$ can be different structures, referring to Dammann (binary) gratings, sinusoidal gratings, and Fourier gratings [39-41]. Fourier gratings achieve a higher efficiency compared to the other two kinds and are relatively easy to fabricate. Therefore, Chapter 4 in this thesis concentrates on modeling, designing and characterizing Fourier gratings. A Fourier grating refers to a phase grating whose phase modulation function is expanded into a Fourier series. To simplify the mathematics, we first look at the one dimensional case where $\Delta\phi$ and t only depend on x_0 .

$$\Delta\phi(x_0) = \sum_{n=1}^N a_n \cdot \cos(n \frac{2\pi}{D} x_0), \quad (2.17)$$

$$t(x_0) = \exp\left(i \sum_{n=1}^N a_n \cdot \cos\left(n \frac{2\pi}{D} x_0\right)\right) = \prod_{n=1}^N \exp\left(i a_n \cdot \cos\left(n \frac{2\pi}{D} x_0\right)\right), \quad (2.18)$$

where D is the size of one period of the grating, and a_n is a set of Fourier coefficients, the value of which determines the surface structure of the grating, thus the diffraction pattern. Therefore, the work is to find a set of a_n that generates a grating to produce the diffraction pattern of multiple beams. The Fourier transform of $a_1 \cdot \cos(2\pi x_0/D)$ is known [38]:

$$\mathcal{F}\left\{a_1 \cdot \cos\left(\frac{2\pi}{D} x_0\right)\right\} = \sum_{-\infty}^{\infty} J_q(a_1) \delta\left(\frac{x}{\lambda z} - \frac{q}{D}\right), \quad (2.19)$$

where J_q denotes the Bessel function of the first kind of order q . So the Fourier transform of the transmission function $t(x_0)$ is:

$$U(x, z) = A \times \otimes_{n=1}^N \left[\sum_{-\infty}^{\infty} J_q(a_n) \delta \left(\frac{x}{\lambda z} - \frac{nq}{D} \right) \right]. \quad (2.20)$$

The factor A is the product of the amplitude of the incoming light and the phase component in front of the integral symbol in Eq. 2.15. From Eq. 2.20, for an incoming beam with a Gaussian distributed amplitude, the far field diffraction pattern of the Fourier grating is a multiple Dirac delta function with a Gaussian beam envelope. By adjusting the values of a_n , one can design a Fourier grating with a certain number of pixels. Since it is impractical to get a_n directly from Eq. 2.20, the Fast Fourier Transform (FFT) algorithm in Matlab is applied to find the a_n [42]. Using FFT algorithm on the transmission function $t(x_0)$ in Eq. 2.18, a set of complex coefficients b_i is obtained and the product of these complex coefficients and their conjugate $b_i b_i^*$ is the intensity of the multiple Dirac delta function. By searching the proper set of a_n , the desired number of $b_i b_i^*$, e.g. for a 9-pixel grating $b_i b_i^* = [\dots, 0, 0, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, 0, 0 \dots]$, can be obtained. The detailed design, fabrication, and characterization of the Fourier grating is described in Chapter 4.

2.3 Hot Electron Bolometer Mixer

This section introduces the working principles of a hot electron bolometer mixer, the main characterization parameters of HEB mixers, and the measurement techniques to characterize HEB mixers.

2.3.1 Working principle of a bolometer as a mixer

When radiation power P_0 irradiates a bolometer, it is absorbed by the absorber, the temperature of which increases and is measured by a thermometer. The absorber's ability to store heat is indicated by its heat capacity C . The absorber is connected to the heat sink by a weak thermal link, through which the increased part of the temperature of the absorber is transferred to the heat sink with a temperature T_{bath} . The heat transfer efficiency of the weak thermal link is determined by the thermal conductance G .

Figure 2.6. Schematic picture of a bolometer. After the power of the incident radiation is absorbed by the absorber, the thermometer detects the change of temperature in the absorber by the change of its resistance. The weak thermal link is used to cool down the absorber by transferring heat from the absorber to the heat sink.

For a time varying incident power $P(t)$, the temperature change of the absorber T_b can be expressed by the heat balance equation:

$$P(t) = C \frac{dT_b}{dt} + G(T_b - T_{bath}). \quad (2.21)$$

Solving this equation for a sinusoidal input power at frequency ω , the temperature of the absorber T_b can be obtained:

$$T_b = \left(\frac{P(t)}{G} + T_{bath} \right) (1 + \omega^2 \tau^2)^{-1}, \quad (2.22)$$

where $\tau = C/G$ is the time constant of the bolometer. When the bolometer is used as a mixer, this time constant determines the IF bandwidth ($\Delta\omega = 1/\tau$) [43]. In an electrical resistance thermometer, the change of the temperature is transferred to a change of the resistance. With a biased current, a voltage change is measured in the end. With the celestial signal P_S and the LO signal P_{LO} irradiating the bolometer, the voltage across the bolometer can be expressed as:

$$V(t) = V_S \cos(\omega_S t) + V_{LO} \cos(\omega_{LO} t), \quad (2.23)$$

where V_S and V_{LO} are the voltages corresponding to the celestial signal and the LO signal respectively. Here ω_S and ω_{LO} are the frequency of the celestial signal and the LO signal. Assuming the resistance of the bolometer is R_0 , the instantaneous RF power dissipated on the bolometer is:

$$P(t) = \frac{V^2(t)}{R_0}. \quad (2.24)$$

Taking Eq. 2.23 to 2.24 and with $P_{LO} = V_{LO}^2/2R_0$ and $P_S = V_S^2/2R_0$ we can get:

$$P(t) = P_{LO} + P_S + P_{LO} \cos(2\omega_{LO}t) + P_S \cos(2\omega_S t) + 2\sqrt{P_{LO}P_S} \cos((\omega_{LO} + \omega_S)t) + 2\sqrt{P_{LO}P_S} \cos((\omega_{LO} - \omega_S)t). \quad (2.25)$$

The thermal response of the HEB mixer is not fast enough to follow the high frequency (THz) terms, $2\omega_S$, $2\omega_{LO}$, and $\omega_{LO} + \omega_S$, but it responds to the intermediate frequency (IF) $\omega_{IF} = |\omega_{LO} - \omega_S|$. Furthermore, the celestial signal is much smaller than the LO signal. Therefore, the RF power dissipated on the bolometer can be written as:

$$P(t) = P_{LO} + 2\sqrt{P_{LO}P_S} \cos(\omega_{IF}t). \quad (2.26)$$

As described in Section 1.2, the mixer has an upper and a lower sideband where the celestial signal frequency is higher or lower than the LO frequency. For the mixers demonstrated in this thesis, the intermediate frequency in both sidebands is measured and this kind of mixer is called a double sideband (DSB) mixer.

2.3.2 Phonon-cooled HEB mixer

A hot electron bolometer (HEB) makes use of either electron-phonon interaction or the electron diffusion to the contact pads connected to the bolometer bridge to cool down the “hot electrons” in the mixer [44]. The cooling process allows the HEB to continuously receive the celestial signal. For a phonon-cooled HEB mixer, the superconducting film acts as the absorber, and the substrate acts as the heat sink, as depicted in Figure 2.7. The superconducting film is deposited on the substrate and the boundary resistance between the film and the substrate acts as a thermal link [45].

Figure 2.7. Phonon-cooled hot electron bolometer mechanism [46]

The incident power heats the electrons to a temperature T_e , and the hot electrons transfer their thermal energy to the phonons with the time τ_{e-ph} . The temperature of the phonons increases to T_{ph} , and they transfer the thermal energy back to the electrons with the time τ_{ph-e} . In the next step, the phonons escape to the substrate and transfer their thermal energy to the substrate in a time τ_{esc} . To effectively cool down the hot electrons, the transfer time from the electrons to the phonons τ_{e-ph} is far shorter than the transfer time from the phonons to the electrons τ_{ph-e} . The phonon escape time τ_{esc} must be much shorter than τ_{e-ph} to prevent heat accumulation in the phonon system and to cool down the phonons effectively. The total electron relaxation time is:

$$\tau_\theta = \tau_{e-ph} + \frac{c_e}{c_{ph}} \tau_{esc} , \quad (2.27)$$

where c_e and c_{ph} are the specific heats of the electrons and the phonons respectively, which are temperature dependent. The τ_{e-ph} is also temperature dependent and can be written as [47]:

$$\tau_{e-ph} \propto T^{-n}. \quad (2.28)$$

The exponent n depends on material properties. For example, the τ_{e-ph} of MgB₂ devices demonstrated in [45] is 3.5 ps and 6 ps for a critical temperature $T_c=39.5$ K and $T_c=31$ K respectively. The phonon escape time τ_{esc} is determined by the thickness of the film d , the speed of sound u and the film/substrate acoustic phonon transmission coefficient β .

$$\tau_{esc} = \frac{4d}{\beta u} . \quad (2.29)$$

Decreasing the thickness of the superconducting film reduces the phonon escape time. However, the decrease of the film thickness will cause a decrease of the critical temperature of the film, which will increase τ_{e-ph} . In practice, the superconducting film has a minimal thickness of ~ 5 nm. Below this thickness, the superconductivity of the film becomes unstable, thus the film becomes unreliable. A short electron relaxation time is essential to increase the IF bandwidth of the HEB. Therefore it is desirable to have a ultrathin superconducting film with a relatively high T_c .

2.3.3 Conversion gain

The conversion gain is an important characteristic of the mixer, and is defined as the ratio between the IF output power P_{IF} and the incident RF signal power P_S . The equation of conversion gain is given as [48,49]:

$$G_m = \frac{P_{IF}}{P_S} = \frac{2R_L P_{DC} P_{LO} C_{rf}^2}{R_0(R_0 + R_L)^2 (1 - C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0})^2} \frac{1}{1 + (\omega \tau_{mix})^2}, \quad (2.30)$$

where I_0 is the bias current, R_0 and R_L are the resistance of the bolometer at the operating point and of the IF load respectively, and C_{rf} and C_{dc} are defined as:

$$C_{dc} = \frac{\delta R}{\delta P_{dc}} \big|_{\delta P_{rf}=0}, \quad (2.31)$$

$$C_{rf} = \frac{\delta R}{\delta P_{rf}} \big|_{\delta P_{dc}=0}. \quad (2.32)$$

For a given HEB mixer, C_{dc} and C_{rf} can be calculated using hot spot models[49]. The τ_{mix} is the time constant of the mixer, which determines the gain bandwidth of the mixer f_g , defined as the frequency where the conversion gain drops by a factor of 3dB.

$$\tau_{mix} = \frac{\tau_\theta}{1 - C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0}}, \quad (2.33)$$

$$f_g = \frac{1}{2\pi \tau_{mix}}, \quad (2.34)$$

where τ_θ is the electron temperature relaxation time, as described in Eq. 2.27. Combining Eq. 2.30 and Eq. 2.34 and using $\omega=2\pi f_{IF}$, we get the following equation:

$$G_m = \frac{P_{IF}}{P_S} = \frac{2R_L P_{DC} P_{LO} C_{rf}^2}{R_0(R_0 + R_L)^2 (1 - C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0})^2} \frac{1}{1 + (\frac{f_{IF}}{f_g})^2}. \quad (2.35)$$

Higher RF frequency mixers need a wider gain bandwidth for astronomical observation, for example, the same velocity resolution for a Doppler shifted line at 5 THz requires a 5-times greater IF gain bandwidth than at 1 THz [50].

2.3.4 Noise temperature

In radio astronomy, the noise is not expressed as noise power, but as a noise temperature. Their relation is:

$$T_M = \frac{P}{k_B B}, \quad (2.36)$$

Where T_M is the noise temperature of the mixer, P is the noise power of the mixer, k_B is the Boltzmann constant, and B is the total bandwidth over which the noise power is measured. The noise temperature is proportional to the noise power, so we can get the noise power by measuring the noise temperature and using Eq. 2.36.

There are two main noise sources in an HEB mixer: Johnson noise and thermal fluctuation noise (or phonon noise). The Johnson noise is a fundamental form of thermodynamic noise, caused by the random thermal motions of electrons in the HEB. The thermal fluctuation noise is caused by the random exchange of energy across the weak thermal link between the detector and the bath. The contribution of the Johnson noise and the phonon noise to the total output noise is [43]:

$$T_{Jn}^{out} = \frac{4R_L R_0 T_e}{(R_0 + R_L)^2 (1 - C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0})^2}, \quad (2.37)$$

$$T_{FL}^{out} = \frac{I_0^2 R_L}{(R_0 + R_L)^2 (1 - C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0})^2} \left(\frac{\partial R}{\partial T} \right)^2 \frac{4T_e^2}{c_e V} \tau_\theta \frac{1}{1 + (\omega \tau_\theta)^2}, \quad (2.38)$$

thus the total output mixer noise temperature is:

$$T_{mix}^{out} = T_{Jn}^{out} + T_{FL}^{out}. \quad (2.39)$$

The input noise temperature of the DSB mixer is obtained by dividing the output noise by the DSB mixer conversion gain:

$$T_{mix}^{in} = \frac{T_{Jn}^{out} + T_{FL}^{out}}{G_m^{DSB}(0)(1 + (\frac{f_{IF}}{f_g})^2)^{-1}} = \frac{T_{Jn}^{out} + T_{FL}^{out}}{G_m^{DSB}(0)} (1 + (\frac{f_{IF}}{f_g})^2), \quad (2.40)$$

Where $G_m^{DSB}(0)$ is the mixer conversion gain when $f_{IF} = 0$. From the above equation we find that a higher IF frequency leads to a higher noise temperature, and a large gain bandwidth reduces this influence. In this thesis, we measure the

receiver noise bandwidth, which is the IF where the receiver noise temperature becomes twice the noise temperature near the zero IF frequency. The receiver noise temperature includes the noise temperature contribution from the IF chain T_{IF} . The relation between the noise bandwidth f_n and the gain bandwidth f_g is [51]:

$$f_n \approx f_g \sqrt{\frac{T_{Jn}^{out} + T_{FL}^{out}(0) + T_{IF}}{T_{Jn}^{out} + T_{FL}^{out}}} . \quad (2.41)$$

From which we see that the noise bandwidth is always larger than the gain bandwidth.

As stated in Section 1.2, a heterodyne receiver system is composed of a front-end and a back-end. The front-end includes a local oscillator, the optics used to combine the LO signal and the celestial signal, a mixer and an IF amplifier chain. The back-end is a spectrometer or a power detector. The noise temperature of the receiver is higher than the noise temperature of the mixer because it includes three elements: optics, mixer and IF amplifier chain. The input DSB receiver noise temperature T_{rec}^{DSB} can be calculated:

$$T_{rec}^{DSB} = T_{opt} + \frac{T_{mix}^{in}}{G_{opt}} + \frac{T_{IF}}{G_{opt}G_m^{DSB}} , \quad (2.42)$$

where T_{opt} is the noise temperature contribution from the optics, and G_{opt} is the gain of the optical components.

2.3.5 Techniques for measuring HEB mixers

This section introduces the techniques to measure the main parameters of an HEB mixer. The current-voltage curves together with the resistance-temperature curve (mentioned in Chapter 1) are the DC properties of a mixer. They can be used to predict the performance of the mixer, as well as verify the quality of the device, since it is found that devices with similar DC properties have a similar performance (within 10%) [25]. We mainly focus on the mixing performance of an HEB in this section, including the sensitivity, conversion gain, and IF bandwidth of an HEB mixer. The sensitivity of an HEB mixer is measured by the Y-factor technique, and the mixer conversion gain is obtained by the U-factor technique. The methods to measure the IF bandwidth are also introduced in this section.

2.3.5.1 Y-factor technique

The Y-factor technique is the most common method to measure the receiver noise temperature [52]. The Y-factor is defined as a ratio between the receiver output power responding to a hot blackbody load P_{hot} and the receiver output power responding to a cold blackbody load P_{cold} :

$$Y = \frac{P_{hot}}{P_{cold}} = \frac{G_{total} k_B (T_{rec} + T_{CW(293K)}) B}{G_{total} k_B (T_{rec} + T_{CW(77K)}) B} = \frac{T_{rec} + T_{CW(293K)}}{T_{rec} + T_{CW(77K)}}. \quad (2.43)$$

In this equation, $G_{total} = G_{opt} \cdot G_m^{DSB} \cdot G_{IF}$ is the total gain of the receiver, and $T_{CW(293K)}$, $T_{CW(77K)}$ are the Callen-Welton temperatures of the hot load and the cold load respectively. According to Callen and Welton[53], and Kerr et al.[54], the relation between the noise temperature of a black body and its physical temperature is:

$$T_{CW} = T_{phy} \left[\frac{hf/k_B T_{phy}}{\exp(hf/k_B T_{phy}) - 1} \right] + \frac{hf}{2k}, \quad (2.44)$$

where T_{CW} is Callen-Welton temperature of the load, and T_{phy} is the physical temperature. The symbol h is the Planck constant and f is the frequency at which the load is observed. Then the receiver equivalent noise temperature can be obtained from Eq. 2.43:

$$T_{rec}^{DSB} = \frac{T_{CW(293K)} - Y \cdot T_{CW(77K)}}{Y - 1}. \quad (2.45)$$

According to Eq. 2.42, the mixer noise temperature can be deduced:

$$T_{mix}^{DSB} = \left(T_{rec}^{DSB} - T_{opt} - \frac{T_{IF}}{G_{opt} G_m^{DSB}} \right) G_{opt}. \quad (2.46)$$

The noise temperature contribution from the optics T_{opt} can be calculated by this equation:

$$T_{opt} = \left(\frac{1}{G_{opt293K}} - 1 \right) \times T_{CW(293K)} + \frac{1}{G_{opt293K}} \times \left(\frac{1}{G_{opt4K}} - 1 \right) \times T_{CW(4K)}, \quad (2.47)$$

where the $G_{opt293K}$ and G_{opt4K} are the gain of the optics at room temperature and cryogenic temperature respectively, while the $T_{CW(293K)}$ and $T_{CW(4K)}$ are the Callen-Welton temperature of the room temperature and cryogenic temperature respectively.

2.3.5.2 U-factor technique

The U-factor is defined as the ratio between the receiver output power when the receiver is in an operating state and when the receiver is in a reference state. A

reference state can be a normal state or a superconducting state. Due to the impedance mismatch between HEB and LNA, which varies as a function of the IF, there are standing waves varying as a function of the IF between the output of the HEB and the input of the LNA. Therefore, the noise temperature of the reference state is not a fixed value, but a value changing as a function of the IF. In our measurement setup, a circulator is put between the HEB mixer the LNA as an isolator, which is essential to give an accurate reference noise temperature T_{ref} to use the U-factor technique. When the HEB is in its superconducting state, the input of the LNA is connected to a 50 Ω resistor (refer to Figure 2.8). Therefore the T_{ref} is equal to the physical temperature of the resistor.

$$U = \frac{P_{hot}}{P_{ref}} = \frac{G_{total}(T_{rec}^{DSB} + T_{293K})k_B B}{G_{IF}(T_{IF} + T_{ref})k_B B} = \frac{G_{opt}G_m^{DSB}(T_{rec}^{DSB} + T_{293K})}{T_{IF} + T_{ref}}. \quad (2.48)$$

Combining this equation with Eq. 2.45, the mixer conversion gain G_m^{DSB} can be obtained. Furthermore, knowing the input noise temperature of the mixer and the mixer conversion gain, the output noise of the mixer can be obtained:

$$T_{mix}^{out} = \frac{T_{mix}^{in}}{G_m^{DSB}}. \quad (2.49)$$

Figure 2.8. Equivalent circuit model for the circulator placed between the mixer and the LNA [55]. The circulator has three ports, and when port 3 is terminated with a 50 Ω resistor, the circulator works as an isolator. An input signal at port 1 will pass to and exit port 2 and any reflected signal will be passed to port 3 and absorbed by the load. This prevents the formation of the standing waves between the HEB mixer and the LNA.

2.3.5.3 IF bandwidth

To measure the IF bandwidth of the HEB mixer, two methods could be used. The first is to use two THz sources, one with a fixed frequency as the LO and another with a tunable frequency as the signal source. Tuning the frequency of the signal

source and measuring the corresponding conversion gain or the receiver noise temperature as the function of IF frequency, one can get the gain bandwidth or the noise bandwidth. However, it is not easy to find a tunable source with a relatively wide frequency range in the THz and in particular at the high end of THz frequencies. Thus in this thesis we use another method, which records the receiver output power P_{hot} and P_{cold} as a function of the IF when the HEB mixer is at the optimal operating point and responds to a hot blackbody load and a cold blackbody load. Using the Y-factor technique, the receiver noise temperature as a function of the IF can be obtained. Therefore the noise bandwidth f_n is measured.

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Chapter 3

3.9 THz spatial filter based on a back-to-back Si-lens system

Based on

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We present a terahertz spatial filter consisting of two back-to-back (B2B) mounted elliptical silicon lenses and an opening aperture defined on a thin gold layer between the lenses. The beam filtering efficiency of the B2B lens system is investigated by simulation and experiment. Using a unidirectional antenna coupled 3rd-order distributed feedback (DFB) quantum cascade laser (QCL) at 3.86 THz as the source, the B2B lens system shows 72% transmissivity experimentally with a fundamental Gaussian mode as the input, in reasonably good agreement with the simulated value of 80%. With a proper aperture size, the B2B lens system is capable of filtering the non-Gaussian beam from the QCL to a nearly fundamental Gaussian beam, where Gaussicity increases from 74% to 99%, and achieves a transmissivity larger than 30%. Thus, this approach is proven to be an effective beam shaping technique for QCLs, making them to be suitable local oscillators in the terahertz range with a Gaussian beam. Besides, the B2B lens system is applicable to a wide frequency range if the wavelength dependent part is properly scaled.

3.1 Introduction

Heterodyne detection, which makes use of a mixing detector and a high power local oscillator (LO), measures the light intensity together with an exceptionally high spectral resolution. In astronomy, this technique is widely used to study atomic fine structure lines and molecular rotational lines at terahertz frequencies (0.3-10 THz) [1]. At supra-terahertz frequencies (> 1 THz), the available heterodyne detectors include Schottky diodes [2], hot electron bolometers (HEB) [3], terahertz quantum well photodetectors (QWP) [4], and quantum cascade laser (QCL) detectors, which can be used for dual-comb multiheterodyne detection [5-7]. HEB mixers, due to their high sensitivity, are the choice of heterodyne detector for astrophysics. Waveguide-based HEB mixers have been used up to 4.7 THz in the heterodyne spectrometers GREAT (German REceiver for Astronomy at Terahertz frequencies) and upGREAT on the Stratospheric Observatory for Infrared Astronomy (SOFIA) [8]. In the frequency range > 1 THz, a quasi-optical approach based on a lens-antenna is commonly used to couple THz radiation from an LO source to a detector [3]. Typically a THz quantum cascade laser (QCL) acts as the LO, while the mixer is a superconducting HEB, integrated with a planar antenna on a lens [9]. Additionally, to match the beam from the source to the mixer, a few lenses or reflective mirrors are included in the optical path. A QCL is the most promising LO source at supra-terahertz frequencies due to its high output power. Current THz QCLs have been demonstrated to cover the frequency range from 1.2 THz to 5.0 THz, and their output powers reach more than 200 mW in continuous-wave mode and watt level in pulsed mode [10-13], which is sufficient as an LO for a heterodyne array with more than 100 mixers. One of the QCL designs, the third order distributed-feedback (DFB) laser structure based on double metal waveguide designs, is being implemented for heterodyne instruments, with a single-mode emission, a high-temperature operation, and a relatively narrow beam [14]. The angular divergence of its beam is $\sim 10^\circ$ and $\sim 25^\circ$ in orthogonal directions, which are within 30° from the propagation axis, meeting the criterion of the validity of the paraxial approximation when using a Gaussian optics analysis according to [15]. However, the beams of QCLs deviate considerably from a fundamental Gaussian shape. A fundamental Gaussian beam is essential in terms of effective coupling of the radiation to lens-antenna mixers, the far field of which is nearly fundamental Gaussian beam [16,17]. Furthermore, it reduces stray light, caused by reflections from optical components, and makes the optical design for an instrument system more accurate. In order to improve mapping speed, heterodyne array receivers with multiple mixers at supra-THz frequencies have been developed, e.g. for the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) [18,19]. For heterodyne mixer

arrays, phase gratings are used as the multiplexer, which diffracts a single QCL beam into multiple beams as an array LO [20] and recently reported up to 81 beams [21]. To avoid overlap between the individual diffracted beams, a Gaussian input beam to the grating is required [22,23].

QCL based on the surface plasmon design has a better output beam, but has the disadvantage of a relatively low operation temperature. Such an approach has been successfully implemented for the 4.7 THz heterodyne spectrometer GREAT on SOFIA although the beam still contains higher-order Gaussian modes [24]. Hollow waveguides or hyper-hemispherical silicon lenses mounted near the exit facet of the QCLs inside the cryostat window achieve a far field single-lobe beam pattern with low divergence, but the beam profile is not ideal and the mechanical robustness can be a concern [25-28]. A combination of a spherical lens and a diaphragm has been used to produce a directive beam with the uniform phase front, from a wire laser [29]. The latter is known to produce a divergent, undirective beam. We are interested in introducing a spatial filter for a THz QCL to form a THz source with not only a high power, but also a fundamental Gaussian beam. A known beam filter is a back-to-back corrugated feedhorn pair, which has been used as a spatial filter to eliminate the high-order Gaussian modes and random fluctuations of a source at microwave frequencies [30]. Such a feedhorn pair has been also manufactured at 2.5 THz and shows an excellent beam pattern [31]. However, the feed horn approach requires precise fine structures to obtain a fundamental Gaussian beam, which is difficult to manufacture at high THz frequencies. Besides, such a structure is inherently narrowband. Therefore, developing a beam filter capable of shaping a non-Gaussian beam into a fundamental Gaussian beam with a good efficiency is highly demanded.

In this work we report a spatial filter based on a back-to-back (B2B) lens system operated at a supra-THz frequency and its characterization using an available high power QCL at 3.9 THz. The beam filtering efficiency of the B2B lens system, which characterizes both the Gaussicity of the output beam and power transmissivity, is studied in both simulation and experiment. Besides, a mechanical lens holder is introduced to align the lens system for optimal performance. Because the available source in our study has a frequency of 3.9 THz, our simulation and experiment will focus on this particular frequency. However, the B2B lens system should be applicable for different wavelengths if the wavelength dependent part is properly scaled.

3.2 Device concept and analysis

3.2.1 Back-to-back lens system

A conventional spatial filter is composed of three separate components, a lens, a pinhole, and a lens [32]. In analogy to that, our B2B lens system is an integrated lens system, where two back-to-back elliptical lenses [33] are contacted via an aperture etched in a thin Au layer, to reduce the silicon-air interfaces through which THz light travels. Thus, the efficiency of the spatial filter is enhanced. One can use a lens and an iris aperture to achieve a quasi-Gaussian beam, as our group did in [21], but the efficiency is very low ($\sim 10\%$). Two off-axis parabolic mirrors combined with a pinhole can also be used as a beam filter with an efficiency of 22% [22], but the system is bulky and the alignment of the whole system is challenging. In our approach, a lens with an elliptical front surface is chosen because it couples well to a Gaussian-beam at its minimum waist [34] and its on-axis beam has no aberrations if the eccentricity is equal to the reciprocal of the refractive index of the lens material [35]. The spatial filter configuration and filtering principle are schematically illustrated in Figure 3.1, where an imperfect laser beam is firstly focused on the focal point of the first lens, the aperture with an appropriate diameter blocks the undesired part of the laser beam, and then the second lens re-collimates the laser beam. In detail, a B2B lens system consists of two high-resistivity ($> 5 \text{ k}\Omega\text{cm}$) silicon (HRSi) lenses, between which there is a piece of a double-side polished HRSi wafer coated with a thin gold layer on one side, where a circular hole, used as the aperture, is lithographically defined in its center that lets only a certain part of the beam pass through. Since gold is highly reflective, it blocks the undesired light from the incoming beam. A thin Ti layer is used for the adhesion of gold on the silicon wafer-piece. The thickness of the gold layer is $200 \pm 3 \text{ nm}$, which is much larger than the penetration depth of $\sim 40 \text{ nm}$ of gold at 3.9 THz. A Si elliptical lens with a 10 mm diameter has been demonstrated to have a good performance when used in a lens antenna [36]. In the B2B lens system, the two lenses have the same diameter of 10 mm and a semi-major axis of 5.23 mm. The lens on the left in Figure 3.1 has an extension of 1.53 mm to focus the incoming beam to its second focal point, while the lens on the right has a reduced extension of 1.25 mm combining with the wafer-piece of 0.28 mm thick, making the focal point at the same position as for the left lens. The wafer-piece is a $10.5 \times 10.5 \text{ mm}^2$ square to cover the entire back surface of the lenses. The optical transmissivity of the air-silicon interface is $\sim 70\%$ [37], causing the total transmissivity of the double lens system to be $\sim 50\%$. To reduce reflection losses, an anti-reflection layer is deposited on the surface of the Si lens. Ideally, the reflection of the incoming

beam into a Si lens is reduced to zero at normal incidence if the refractive index and the thickness satisfy the following relations [37]:

$$n_{AR} = \sqrt{n_{Si}}, \quad (3.1)$$

$$t_{AR} = \frac{(2m+1)\lambda}{4n_{AR}} (m = 0, 1, 2, \dots), \quad (3.2)$$

Figure 3.1. Back-to-back lens system containing two Si lenses and a Si wafer-piece deposited with a thin gold layer. The three components are aligned together. The incoming non-Gaussian beam is first focused by the left lens, then the gold layer blocks the unwanted part. After the right lens a Gaussian beam is obtained.

where n_{AR} is the refractive index of the anti-reflection coating, n_{Si} is the refractive index of silicon, λ is the wavelength of the incoming beam, and t_{AR} is the thickness of the anti-reflection coating. A common choice is Parylene C, which is a thermoplastic polymere with good thermal stability and adhesion properties. Its refractive index is about 1.62, which is close to the ideal value of 1.85, and it has the advantage of being able to coat on small and curved optics with almost any thickness and with high homogeneity [38]. The thicknesses of the Parylene C coatings on the two lens surfaces are measured to be $11 \pm 1 \mu\text{m}$, which is about a quarter of the wavelength of 3.9 THz radiation in Parylene C. When the two lenses and the wafer-piece all are aligned well and contact tightly, without air gaps between the lenses and the wafer-piece, the transmissivity of the lens system is calculated to be 92% using the Fresnel equation [39]. The 8% losses are due to the oblique incidence to the elliptical surface and the difference between the refractive index 1.62 of Parylene C and the ideal refractive index 1.85. However, the absorption coefficients of Parylene C [40] and HRSi need to be considered. Taking the absorption coefficients of Parylene C of 25 cm^{-1} [37] and the absorption coefficient of HRSi of 0.05 cm^{-1} [41] into account, the transmissivity of the lens system is simulated with COMSOL Multiphysics as explained in the next section.

3.2.2 Simulation and expected results

In COMSOL Multiphysics [42], a 2D model of the B2B lens system shown in Figure 3.2 (a) (b) is created to simulate its filtering efficiency. Due to the overloaded calculation for the 10 mm diameter lenses at 3.86 THz, the lenses are rescaled to 4 mm in diameter to facilitate the simulation. In this case, the size of the wafer-piece and the incoming beam are also rescaled proportionally [43]. The incident Gaussian beam is assigned by an input port with a perfectly matched layer (PML), which absorbs the reflected waves. The aperture is simulated by assigning the two boundaries beside the hole as perfect electric conductors (PECs), which reflect waves back totally. With an aperture presented, as in Figure 3.2 (b), part of the wave is reflected back compared to the system without an aperture in Figure 3.2 (a). Therefore, the presence of the aperture influences the transmissivity of the lens system and its output beam profile. The extent of influence depends on the size of the aperture, which will be described later.

Figure 3.2. (a) 2D model of the B2B lens system without apertures in simulation. Different colors indicate the electric field distribution. The inset is the field distribution around the focal point of the lens system. (b) 2D model of the B2B lens system with an aperture in simulation. (c) Schematic of field propagation from the xy plane to the $x'y'$ plane.

With a bare wafer-piece (no PECs assigned) placed in the middle of the lenses and a fundamental Gaussian beam as the input, the output beam is a fundamental Gaussian beam and the transmissivity of the lens system, which is defined as the ratio between the output power from the lens system and the input power, is simulated to be 80% with the anti-reflection coating of Parylene C. Compared to the value of 92% in section 2.1, the loss of 12% is due to the absorption of Parylene C and HRSi. The transmissivity of the lens system without the AR coating is only 49%, implying that the AR coating improves the transmissivity by 31%.

A proper aperture size is essential to effectively filter a non-Gaussian beam into a fundamental Gaussian beam. Let the electric field distribution of the incoming beam be $U(P_0)$, which is in the xy plane as shown in Figure 3.2 (c) and its distribution is within a surface S_0 . Using the first Rayleigh–Sommerfeld diffraction formula [44] the field distribution $U(P_1)$ on the surface of the first elliptical lens can be expressed as:

$$U(P_1) = \frac{i}{\lambda} \iint_{S_0} U(P_0) \cos(\vec{n}_1, \vec{r}_1) \frac{\exp(ikr_1)}{r_1} dS_0. \quad (3.3)$$

Here, $\vec{n}_1$ is the normal vector of the surface S_0 , $\vec{r}_1$ is the vector from P_0 to P_1 , k is the wave number $2\pi/\lambda$, and r_1 is the length of the vector $\vec{r}_1$. Since the first Rayleigh–Sommerfeld diffraction formula requires the diffracting screen to be planar, the more general Fresnel–Kirchhoff diffraction formula [44] is used to calculate the field distribution $U(P_2)$ on the focal plane $x'y'$ of the elliptical lens,

$$U(P_2) = \frac{i}{2\lambda} \iint_{S_1} U(P_1) [\cos(\vec{n}_2, \vec{r}_1) + \cos(\vec{n}_2, \vec{r}_2)] \frac{\exp(ikr_2)}{r_2} dS_1, \quad (3.4)$$

$$I(P_2) = |U(P_2)|^2, \quad (3.5)$$

where S_1 is the surface of the elliptical lens, $\vec{n}_2$ is the normal vector of the surface S_1 , $\vec{r}_2$ is the vector pointing from P_1 to P_2 , and r_2 is the length of the vector $\vec{r}_2$. Computing these two integrals, from the incoming field distribution the field distribution and the beam size on the focal plane of the elliptical lens are obtained. The proper aperture size should be close to the beam size on the focal plane. However, it is difficult to know the field distribution of QCL beams in advance, which deviate from a Gaussian distribution to varying degrees. So our approach is first to fit the nearly collimated non-Gaussian QCL beam in the plane Σ in Figure 3.2 (c) with the Gaussian equation [15] and derive an estimated beam waist ω_{0x} and ω_{0y} (defined as the radius at which the amplitude is $1/e$ of its peak value) in the orthogonal direction. Then the electric field distribution $U(P_0)$ of this fitted Gaussian beam in the xy plane [45] in Figure 3.2 (c) is substituted in Eqs. 3.3-3.5 to calculate the corresponding field distribution in the focal plane, from which the proper aperture size is estimated.

$$U(P_0) = \sqrt{\frac{2}{\pi\omega_x\omega_y}} \exp\left(-\frac{x^2}{\omega_x^2} - \frac{y^2}{\omega_y^2}\right), \quad (3.6)$$

$$\omega_x = \omega_{0x} \sqrt{1 + \left(\frac{\lambda z_0}{\pi\omega_{0x}^2}\right)^2}, \quad (3.7)$$

$$\omega_y = \omega_{0y} \sqrt{1 + \left(\frac{\lambda z_0}{\pi\omega_{0y}^2}\right)^2}. \quad (3.8)$$

To verify the filtering efficiency of the B2B lens system with apertures, a Gaussian beam with sidelobes indicated with the black dashed line (a far field plot) in Figure 3.3 is used as the input beam. Fitting this beam with the Gaussian equation, the waist of the fitted Gaussian beam at the plane Σ is found to be ~ 1.7 mm. We then calculate the waist of the Gaussian beam in the focal plane by using Eqs. 3.3-3.8 with $\omega_{0x}=\omega_{0y}=1.7$ mm. We find the beam waist to be $13.8 \mu\text{m}$, indicating that the proper aperture diameter is around $28 \mu\text{m}$. Figure 3.3 plots the intensity profiles of the output beams in the far field from the B2B lens system with different aperture diameters, which are simulated by COMSOL. In the case of the bare wafer-piece (no aperture), the output beam profile is similar to the input with a reduced power level. By reducing the aperture size from 40 to $10 \mu\text{m}$, the level of the sidelobes in the output beam is affected and starts to be suppressed when the size is $30 \mu\text{m}$, confirming the role of the aperture. It is important to notice that the transmissivity decreases as well. We concentrate on filtering a QCL output to a beam that can better couple to a lens-antenna coupled HEB mixer, which is known to have a Gaussian beam, and one of the impact factors for the coupling efficiency is the Gaussicity of the beam. Therefore, the transmissivity of the B2B lens system and the Gaussicity of the output beam are two main characterizations for the lens system. The transmissivities of the B2B lens system with different aperture sizes and the corresponding Gaussivities [46,47] of the output beams are calculated and summarized in Table 3.1. Combining the intensity profiles in Figure 3.3 with the transmissivities and Gaussivities in Table 3.1, we find that the B2B lens system shows good performance when the aperture diameter is between $15 \mu\text{m}$ and $30 \mu\text{m}$, which agrees well with the estimated aperture diameter of $28 \mu\text{m}$.

Figure 3.3. Intensity profiles of the output beams from the back-to-back lens system with different aperture sizes at the far field. The black solid line indicates the output beam profile from the lens system when there is no gold layer between two lenses. Its profile is identical to the input beam profile, which is indicated with the black dashed line. For better comparison, all intensity values have been divided by the maximum intensity of the input beam.

Table 3.1. Transmissivities and Gausscities of the B2B lens system with different aperture size at 3.86 THz

Aperture size	No aperture	40 μm	35 μm	30 μm
Transmissivity	80.4%	57.3%	48.3%	36.4%
Gausscity	38.7%	79.9%	93.5%	99.8%
Aperture size	25 μm	20 μm	15 μm	10 μm
Transmissivity	32.5%	32.9%	31.9%	17.2%
Gausscity	99.9%	99.8%	99.7%	99.6%

Choosing an appropriate aperture size is also important to effectively filter the higher order Gaussian modes. For instance, if there is a TEM_{11} mode with $\omega_{0x}=\omega_{0y}=1.5$ mm beam waist present in the incoming beam, according to Eqs. 3.7-3.8 its field distribution is expressed as:

$$U(P_0) = \sqrt{\frac{2}{\pi\omega_x\omega_y}} \frac{xy}{\omega_x\omega_y} \exp\left(-\frac{x^2}{\omega_x^2} - \frac{y^2}{\omega_y^2}\right). \quad (3.9)$$

Taking this field into Eqs. 3.3-3.5, the intensity distribution of the beam on the focal plane is obtained. We find that the proper aperture diameter to block this beam is smaller than 14 μm . Table 3.2 illustrates the simulated transmissivities of the B2B lens system to a TEM_{11} Gaussian mode when the aperture size changes from 20 μm to 12 μm . This Gaussian mode is nearly fully blocked by the aperture when its size is smaller than 14 μm . The B2B lens system is therefore capable of filtering higher order Gaussian modes when the aperture diameter is properly chosen.

Table 3.2. Transmissivities of the B2B lens system with different aperture size for TEM_{11} Gaussian mode

Aperture size	20 μm	18 μm	16 μm	14 μm	12 μm
Transmissivity	18.3%	7.7%	2.8%	0.76%	0.19%

3.3 Mechanical lens holder and measurement setup

3.3.1 Mechanical lens holder and alignment procedure

As suggested by the simulations in Section 2, with the lens system well aligned, the transmissivity of the lens system reaches 80.5% for a bare wafer-piece with a fundamental Gaussian input beam. However, once there are air gaps between the wafer-piece and the lenses, the performance degrades and the transmissivity decreases quickly. In practice, the transmissivity remains higher than 70% if the air gap is below 2 μm . Another important issue is that the centers of the two lenses (or the optical axis) and the center of the aperture should be well aligned, otherwise the performance degrades too. The required accuracy depends on the aperture size. According to the simulation, for the 10- μm diameter aperture, the transmissivity changes only 2% if there is 1 μm misalignment. For an enlarged aperture, which will be discussed later on, the effect is smaller and becomes negligible. Therefore our goal is to keep the misalignment as low as 1 μm . A mechanical lens holder is designed dedicatedly to align the lens system to such accuracy. By combining the mechanical lens holder with micromanipulators and a microscope, we can realize an alignment accuracy of 1 μm . The mechanical lens holder and micromanipulators are described in Appendix A, together with a description of the alignment procedure.

3.3.2 THz QCL and Measurement setup

To measure the filtering efficiency of the B2B lens system, a unidirectional antenna-coupled 3rd order distributed feedback (DFB) quantum cascade laser (QCL) at 3.86 THz is applied as a source [14]. Figure 3.4 shows an SEM photo of the laser structure in (a), and the simulated far-field radiation pattern together with the electric field distribution inside the laser in (b). The addition of a “reflector” structure is to redirect the power in the undesired backward direction to the desired forward direction, and thus increasing the output power of this laser by a factor of ~ 2 over a usual bidirectional QCL. The laser used has about 10 mW output power, which is relatively high and favorable for obtaining a high signal to noise ratio in the 2D beam profile measurements. Furthermore, the 3rd order DFB structure improves the output beam pattern, namely less divergent, as shown in Figure 3.4 (c). The beam size is ~ 25 mm in the vertical direction (parallel to the QCL plane) and ~ 15 mm in the horizontal direction, implying an angular full width at half-maximum (FWHM) of 23° and 14° in the respective directions. Obviously, the beam deviates considerably from a fundamental Gaussian beam profile.

Figure 3.5 illustrates the measurement setup schematically, where two versions with different optics between the QCL and the B2B lens system are shown in (a) and (b). The setup in Figure 3.5 (a) is used to measure the transmissivity of the B2B lens system with a bare Si wafer-piece. The QCL is cooled down to ~ 10 K in a pulsed tube cooler. Its emitted beam is collimated by a high-density polyethylene (HDPE) lens and filtered by an iris aperture to produce a Gaussian-like input beam profile with a 3.5 mm beam waist. The iris aperture can produce a nearly Gaussian distributed beam, but the efficiency in this case is so low that most of the power ($\sim 90\%$) from the QCL is blocked. A pyro-electric detector mounted on a 2D scanner stage is used to map the beam pattern. The B2B lens system is mounted on a kinematic mount with adjustable angles in the orthogonal directions, and this mount is installed on a 3-axis precision stage, being able to adjust the position of the lens system with 0.1 mm accuracy. As the first step, the peak intensity of the incoming Gaussian-like beam is measured with the detector. Then, the detector position is fixed. Subsequently, the first surface of the lens system is placed on the beam waist position of the incoming beam, which is 5 cm away from the iris aperture. The positions and angles of the lens system are fine-tuned by the mounted stage until the peak intensity of the output beam is at the same position as the peak intensity of the input beam. In this way, the lens system is well aligned with the input beam. The output beam pattern is scanned at a plane that is 8.6 cm away from the 2nd surface of the lens system (15 cm away from the iris aperture since the length of the lens system is 1.4 cm). After removing the lens system, the detector is moved 1.4 cm closer to the iris aperture to make sure that the optical path in the air is the same, and thus the losses in two cases are the same when calculating the transmissivity of the lens system. Then in this position, the input beam pattern is measured.

Figure 3.4. (a) SEM micrograph of the 3rd-order DFB QCL. (b) Simulated far-field radiation pattern (top) and the corresponding electric field distribution inside the laser (bottom) in arbitrary units. (c) Measured output beam pattern from the QCL in the plane perpendicular to the laser structure in (b) at a distance 3.5 cm from the exit of the QCL. Here y is the vertical direction, being parallel to

the QCL plane, while x is the horizontal direction, being perpendicular to the QCL chip.

Figure 3.5. (a) Measurement setup for testing the transmissivity of the lens system without the gold blocking layer. The QCL is mounted vertically in a pulse tube cooler (cooled to ~ 10 K) and its bias voltage is modulated by a sinusoidal function at 70 Hz using an arbitrary waveform generator. The QCL beam is first collimated by an HDPE lens and filtered by an iris aperture, then goes through the lens system. A pyro-electric detector mounted on a 2D scanner stage is used to map the beam pattern. The received signal is read out by a lock-in amplifier with a 70 Hz sinusoidal function reference. The computer controls the stage and reads out the signal received from the lock-in amplifier. (b) Measurement setup for testing the filtering efficiency of the lens system with different aperture sizes. The QCL beam size is reduced by two high-density polyethylene lenses before the beam goes through the lens system.

Figure 3.5 (b) shows the 2nd version of the setup to test the filtering efficiency of the lens system. Two HDPE lenses are introduced to make the input beam size smaller than the lens diameter. Using the same alignment method as described before, several output beam patterns from the lens system with different aperture sizes and the input beam pattern at the position mentioned above are scanned to calculate the transmissivity of the lens system. The input beam pattern at the plane of the first surface of the lens system (the beam waist position) is also scanned to compare the beam shape change from the input to the output beam.

3.4 Measurements and analysis

3.4.1 Transmissivity of the B2B lens system without an opening aperture

The transmissivity of the lens system with a bare wafer-piece is studied to verify the lens system as well as the AR coating. Figure 3.6 shows intensity image plots of the input Gaussian-like beam in (a) and the output beam from the lens system in (b), where the color corresponds to the intensity. The output beam has almost the same size as the input beam, but vertically and horizontally flipped due to the light propagation inside the lens system. After removing the noise floor caused by the pyro-electric detector itself in both the output beam and the input beam data, the transmissivity is calculated to be 72%, which is lower than 80% from the simulation. The difference is only 8%, therefore the measured transmissivity is an excellent result if the possible loss due to the air gaps, tilt angle, and the offset is taken into account.

Figure 3.6. (a) Intensity image plot of the input beam. (b) Intensity image plot of the output beam from the lens system without the gold layer. The color indicates relative intensity.

As explained in the following analysis, any of the mentioned factor affects the transmissivity. Firstly, although we try to minimize the air gaps between the lenses and the wafer-piece, they cannot be fully removed. To obtain a quantitative impression, the transmissivity change as a function of the air gap size is calculated based on the Fresnel equation [39] and plotted in Figure 3.7 (a). To account for the 8% reduction, the two air gaps will roughly be 2 μm . Secondly, there might be a tilt angle between the beam propagation direction and the optical axis of the lens system. The change of the transmissivity as a function of the tilt angle is simulated and shown in Figure 3.7 (b), where the transmissivity change is slow and is reduced by 8% if the tilt angle reaches 12°. Finally, there might be an offset between the center of the beam (peak intensity)

and the center of the lens system. Figure 3.7 (c) shows the simulated transmissivity change as a function of the offset, where to account for the 8% reduction, the offset reaches about 36% of the lens diameter, being 3.6 mm. Likely, the air gaps are the dominant cause for the 8% reduction in transmission based on the simulations and experimental experience, from which we know that much smaller values of the tilt angle and the offset can be achieved. During the measurement, the humidity change in the lab could also influence the results, which is estimated to be <1%, so it can be neglected.

Figure 3.7. (a) Transmissivity of the back-to-back lens system changes with the thickness of the two air gaps between the lenses and the wafer-piece. (b) Simulated transmissivity changes with a tilt angle between the direction of the beam and the optical axis of the lens system. (c) Simulated transmissivity as a function of the ratio of the offset between the center of the beam and the center of the lens system to the lens diameter. The purple line in (b) and (c) indicates the transmissivity change when there is no aperture between two lenses, and the blue line indicates the transmissivity change when the aperture size is 30 μm . (d) Simulated transmissivity change as the function of the ratio of the misalignment between the aperture center and the lens center and to aperture size. The red, blue, and magenta lines indicate the transmissivity changes when the aperture diameter is 30 μm , 50 μm , 80 μm , respectively.

3.4.2 Filtering efficiency of the B2B lens system with an opening aperture

The bare wafer-piece is replaced by the pieces with different sizes of the aperture to test the filtering efficiency of the B2B lens system. In the meantime, the input beam is changed to a non-Gaussian beam which originates from the same QCL. Since the QCL beam is divergent, its beam size becomes larger than the diameter of the lens system even at the position of the cryostat window. So, two HDPE lenses are necessary to collimate the beam and adjust its size. The beam pattern, measured after the two lenses, is plotted in Figure 3.8 (a), where (a₁) shows the beam intensity pattern on the linear scale and (a₂) shows the two 1D cuts in the diagonal and anti-diagonal directions on the decibel scale. They confirm the non-Gaussian distribution, but the beam becomes more symmetric compared to the original beam taken directly from the QCL as shown in Figure 3.4 (c). The reason is that due to the limited diameter of the 1st lens in Figure 3.5 (b) the outer part of the QCL beam is not collected. As described in Section 2, we fit this beam with a Gaussian profile, derive beam waists in two directions ($\omega_{0x}=3.3$ mm, $\omega_{0y}=3.8$ mm), and get the beam waist ($\omega_x=16.3$ μ m, $\omega_y=15$ μ m) in the focal plane by Eqs. 3.3-3.5. Thus, the optimal aperture size for filtering this beam is expected to be around 30 μ m. An aperture much larger than this size is not capable of filtering the undesired components, and an aperture much smaller than this size blocks the desired components of the beam. Figure 3.8 (b₁) (c₁) (d₁) plot the output beam intensity patterns with 30 μ m, 50 μ m, and 80 μ m aperture size on a linear scale, respectively, and (b₂) (c₂) (d₂) plot their 1D cuts in the diagonal and anti-diagonal directions on a decibel scale. When the size-shaped beam propagates through the lens system with the 30 μ m aperture, as shown in Figure 3.8 (b), the output beam is much improved and becomes circular. With the aperture size increases to 50 μ m and 80 μ m, the output beams become less circular and begin to deviate from a fundamental Gaussian beam. Due to the long scanning time, only the main part of the output beam is measured, but the sidelobe level in the output beam is found to be low ~ -20 dB from Figure 3.8 (b₂). To quantify the filtering efficiency by different apertures, the transmissivities and Gaussivities of the B2B lens system are calculated and summarized in Table 3.3.

Figure 3.8. (a₁)(a₂) Intensity plot of the input beam in the plane of the first surface of the lens system on the linear scale and its 1D profiles in the diagonal and anti-diagonal directions on the decibel scale. (b₁)(c₁)(d₁) Intensity plots of the output beams from the lens system at a distance 8.6 cm away from the last surface of the lens system on the linear scale when the aperture diameter is 30 μm, 50 μm, and 80 μm respectively. They share the same color scale. (b₂)(c₂)(d₂) 1D profiles of the output beams in the diagonal and anti-diagonal directions on the decibel scale when the aperture size is 30 μm, 50 μm, and 80 μm respectively. They share the same y label.

Table 3.3. Transmissivities and Gaussivities of the lens system with different aperture size at 3.86 THz

Aperture size	30 μm	50 μm	80 μm	No aperture
Transmissivity	31%	34%	43%	72%
Gaussicity	99%	98%	96%	74%

The transmissivities of the B2B lens systems with 30 μm, 50 μm, and 80 μm apertures are 31%, 34%, and 43% after removing the noise floor caused by the pyro-electric detector itself in the data of both beams. They are also influenced by the three factors mentioned in Section 4.1, from which we conclude that the dominant factor is the air gaps between the lenses and the wafer-piece. However, the B2B lens system with an aperture is more sensitive to the tilt angle than to the offset because different incident angles cause changes in the directions of the refracted beams inside the silicon, which causes the focus to shift from the center of the silicon lens focal plane. Without an aperture, this influence is relatively small, but with an aperture, a small deviation of the focus from the center of the focal plane causes the light to be blocked. For the situation with an

offset, the transmission loss is related to the increase on the light path inside the AR coating but the focus is still on the center of the silicon lens focal plane. To give an intuitive impression, the transmissivity changes for the B2B system with a 30 μm aperture as a function of tilt angle and offset when the incoming beam is a fundamental Gaussian beam are simulated and plotted in Figure 3.7 (b) (c), as indicated with blue lines. The transmissivity drops nearly to 0 with a 2° tilt angle, which proves that there is still room to improve the transmissivity of the B2B lens with careful alignment in the measurements. Besides, the transmissivity is also impacted by the misalignment between the center of the lenses and the center of the aperture caused by the alignment procedure. Figure 3.7 (d) plots the simulated transmissivity changes of the lens systems with 30 μm , 50 μm , and 80 μm apertures as a function of the ratio between the misalignment and the aperture size when the input beam is a fundamental Gaussian one. Since the misalignments of the lens systems for 30 μm , 50 μm , and 80 μm aperture are measured to be 2 μm , 4 μm , and 2 μm respectively, these misalignments cause negligible influence on the transmissivity of the lens system.

The Gaussicity of the lens system is 99%, 98%, and 96% for 30 μm , 50 μm , and 80 μm respectively. The highest Gaussicity comes from the aperture size of 30 μm although the differences between the three are small. All the Gaussicities of the output beams are considerably higher than that of the input beam, confirming that the B2B lens system can effectively filter a non-ideal input beam to a Gaussian beam and even close to a perfect Gaussian beam. The B2B lens system with 30 μm aperture is most favorable for this QCL beam by taking both the Gaussicity and transmissivity into account.

QCLs do not usually generate an ideal beam. It is therefore an interesting question to know how much fundamental Gaussian component is contained in the non-ideal beam power. A by-product of our study with this QCL is to determine this quantity. When the output QCL beam is resized with two lenses, the B2B lens system with the 30 μm aperture can filter and result in 31% power from the input beam to the fundamental Gaussian beam. However, we know a fundamental Gaussian beam will have a transmissivity of 80% by passing through the B2B lens system as simulated in section 2.2, with a 20% loss. Therefore this 31% should be divided by 0.8, leading to $\sim 39\%$, that is the fundamental Gaussian component of the resized QCL beam. Unfortunately, we cannot determine the Gaussian component of the original QCL beam since its outer part was lost due to the limited diameter of the first lens.

No measurements have been done to illustrate the broadband performance of the B2B lens system. But we model the transmissivity of the B2B lens system (the AR coating is optimized for 3.86 THz) by varying the frequency of the

incoming beam from 3 THz to 5.4 THz and we find a maximal drop of 10% within this frequency range. Therefore, we conclude that the B2B lens system has a wide bandwidth (at least 62 %), which should be sufficient for most astronomical applications.

3.5 Conclusions

We report a novel THz spatial filter that consists of two back-to-back elliptical silicon lenses and an aperture in between, formed by a thin gold blocking layer on a silicon wafer-piece. Combining a designed mechanical lens holder and micro-manipulators, we can align the lenses and the aperture with an accuracy of 1 μm . The performance of the lens system with and without aperture is experimentally characterized using a third order DFB QCL at 3.86 THz. When the input beam is Gaussian, the intensity profile of the output beam from the lens system without the gold layer is nearly the same as the input beam and the transmission of the lens system is measured to be 72%, close to the simulated transmission of 80%. With a non-Gaussian beam as an input, the lens system with an aperture shows an output beam with a Gaussicity reaching 99% and a transmission of larger than 30% from the input beam. The latter depends also strongly on the input beam profile. Here we demonstrate the B2B lens system at 3.86 THz because of the availability of a source. This concept can be applied to any other THz frequencies by optimizing the AR coating thickness and adjusting the aperture size. Thus, we show that by combining a B2B lens system with a QCL one can generate an LO with not only high output power but also a fundamental Gaussian beam, which is required for heterodyne receivers at supra-THz frequencies, in particular array receivers, for the airborne observatory of SOFIA [19], the coming balloon borne observatory of GUSTO [18], and the proposed space mission of Origins Space Telescope [48].

Appendix A

Figure 3.9 (a), (b), and (c) show a 3D model of the mechanical lens holder for our B2B lens system, its top view, and its cross-section, respectively. The mechanical lens holder is placed on a movable stage of an optical microscope, which is equipped with three micro-manipulators, allowing for fine tuning of the stage in two orthogonal directions. The three micro-manipulators equipped with digital displays have an accuracy of 1 μm . The flat (or back) part of two lenses and both sides of the wafer-piece are cleaned with acetone and isopropylalcohol in a clean-room environment to prevent particles on the surfaces. The bottom lens is first placed on the support structure in blue in Figure 3.9. The structure in red under the blue only functions as a holder to

prevent the bottom lens from potential damage. To fix the position of the bottom lens, a small screw next to the extension part of the lens is used to push it against the two small pins next to the wafer-piece. After the position of the bottom lens is fixed, the center of the bottom lens is found and marked by the crossline of the microscope eyepiece. Then the wafer-piece is placed on top of the bottom lens and 2 brown clips on the diagonal positions are loosely fastened by 2 screws to push the wafer-piece down, leaving the other two corners for adding glue. The part in dark gray in Figure 3.9 (a) is movable and 5 metal strips shown in orange color are mounted on it. These 5 metal strips keep the wafer-piece in position by pushing it from all sides. The three micro-manipulators in Figure 3.9 (d) are used to move the dark gray part to change the position of the wafer-piece until the center of the aperture is in the same position as the center of the bottom lens. Then the wafer-piece is glued through the two corners without brown clips on the blue part. After the glue is dried, the two brown clips and five metal strips are removed and the top lens is placed on top of the wafer-piece. A screw next to its extension part is also used to push it against the two pins to make sure it is in the same position as the bottom lens, as in Figure 3.9 (b). Four brown clips are fastened by four screws and used to push the top lens down. Then the outer part of the blue structure is removed and the B2B lens system, as shown in Figure 3.9 (e), is ready for an optical test.

Figure 3.9. (a) Designed 3D model of the mechanical lens holder. (b) Top view of the mechanical lens holder. (c) Cross-section of the mechanical lens holder. The flat parts of the lenses and the Si wafer-piece are cleaned and the bottom lens is placed on the blue structure. The Si wafer-piece is placed on top of the bottom lens and then the top lens is placed on top of the Si wafer-piece. (d) Real photo of the mechanical lens holder. Three micro-manipulators are used to adjust the position of the Si wafer-piece to make its center coincide with the center of the bottom lens. After aligning the centers of the lens and the wafer-piece, the wafer-piece is glued to the mechanical lens holder from the two corners without brown clips. (e) After aligning the two lenses and the Si wafer-piece, the outer part is removed and the inner part is used in an optical system.

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Chapter 4

81 Supra-THz beams generated by a Fourier grating and a quantum cascade laser

Based on

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Large heterodyne receiver arrays (~ 100 pixel) allow astronomical instrumentations mapping more area within limited space mission lifetime. One challenge is to generate multiple local oscillator (LO) beams. Here, We succeeded in generating 81 beams at 3.86 THz by combining a reflective, metallic Fourier grating with an unidirectional antenna coupled 3rd-order distributed feedback (DFB) quantum cascade laser (QCL). We have measured the diffracted 81 beams by scanning a single pyroelectric detector at a plane, which is in the far field for the diffraction beams. The measured output beam pattern agrees well with a simulated result from COMSOL Multiphysics with respect to the angular distribution and power distribution among the 81 beams. We also derived the diffraction efficiency to be $94\pm 3\%$, which is very close to what was simulated for a manufactured Fourier grating (97%). For an array of equal superconducting hot electron bolometer mixers, 64 out of 81 beams can pump the HEB mixers with similar power, resulting in receiver sensitivities within 10%. Such a combination of a Fourier grating and a QCL can create an LO with 100 beams or more, enabling a new generation of large heterodyne arrays for astronomical instrumentation.

4.1 Introduction

Radiation at terahertz (THz) frequencies, broadly defined as the 0.3 THz – 10 THz range, has attracted wide interest for applications in astronomical instrumentation, biomedicine, plasma diagnostics and homeland security [1]. Compared to THz direct detection techniques, heterodyne detection, combining a mixer with a local oscillator (LO) to convert a THz frequency radiation line to a lower frequency $\sim$ GHz signal, has the advantages of extremely high spectral resolution together with a quantum noise limited sensitivity. These characteristics make heterodyne detection a powerful technique in astronomical instrumentations to resolve the velocity information from molecular rotational lines and atomic fine structure lines at THz frequencies in the interstellar medium (ISM). For examples, velocity-resolved large-scale images in the fine-structure line of ionized carbon [CII] at 1.9 THz, observed by a 14-pixel heterodyne array receiver on the Stratospheric Observatory For Infrared Astronomy (SOFIA) [2], provide an observational diagnostic for the radiative energy input and the dynamics of the interstellar medium around massive stars [3]. The [CII] spectral line from the Stratospheric THz Observatory 2 (STO2), which is equipped with a 2-pixel heterodyne array, is compared with other fine structure lines to investigate the kinematics of the Trumpler 14 region in the Carina Nebula Complex [4].

In the applications for homeland security, heterodyne techniques can be useful for both active imaging and passive imaging system [5]. A heterodyne imaging system is attractive because such a system detects not only the intensity, but also the phase, making the detection more decisive than the direct detection [6]. Both astronomical and homeland security applications will benefit from a heterodyne array to increase the imaging speed or observation efficiency [7]. Currently, due to the high power consumption in the backend of a heterodyne receiver, including low noise amplifiers and spectrometers, and the needs of the local oscillator (LO) array [8], the practical heterodyne receivers operating at supra-THz (> 1 THz) are limited to an order of 10 pixels. With recent advances in backend technology, involving low-noise-amplifiers [9] and CMOS digital spectrometers [10], both of which have demonstrated impressively low power consumptions, one can envision large heterodyne arrays, for example, 100 pixels or more, for future astronomical instrumentations in space. This allows for mapping more regions of astronomical interest within a space mission lifetime compared to current heterodyne arrays. Similar statements also apply to ground-based telescopes especially at frequencies where suitable weather conditions are rare. The challenge to develop large arrays now is to generate a large LO array with sufficient power and good uniformity among individual beams [11]. In comparison with LO sources based on multipliers [12], quantum

cascade lasers (QCLs) are a more promising LO source in the supra-THz region due to its high output power. Current QCLs working at supra-THz frequencies have been demonstrated to cover the range from 1.2 THz to 4.9 THz, and their output powers typically are milliwatts or more [13], which is sufficient as an LO for a heterodyne array with more than 100 mixers. Besides, the distributed-feedback (DFB) laser structures based on double metal waveguide designs allow single-mode emission and high-temperature operation [14]. Therefore, multiplexing a single beam from a QCL by a diffraction grating to generate an LO array is an attractive approach for large heterodyne arrays.

A phase grating has played a crucial role in optics-related science and applications, including orbital angular momentum beams for optical communications, chromatic broadband nulling, UV and terahertz beam multiplexing, and complex beam shaping [15-19]. A phase grating is a periodic structure converting a single coherent radiation beam into multi-beams in different directions by manipulating the phase of the input beam. In [20], Dammann and Görtler proposed gratings with binary groove shapes, called Dammann gratings, and also structures with continuous phase-only groove shapes. Compared to a Dammann grating, a grating with a continuous phase-only groove shape achieves a higher diffraction efficiency, which is defined as the ratio between the power diffracted into the desired orders and the power of the input beam. The use of a Fourier synthesis technique to achieve the continuous phase-only groove shapes was proposed by Schmahl [21], and gratings having a fundamental and a finite number of harmonics are called Fourier gratings [22]. Better milling tool permits fabrication of Fourier gratings with finer features, thus higher diffraction efficiency. In essence, such a structure can also be viewed as a metasurface, manipulating the phase of the incoming beam [23]. Lanigan et al. fabricated a 3-pixel Fourier grating at 0.1 THz [24]. Graf and Heyminck [25] demonstrated an 8 beams grating operated at 490 GHz with a measured diffraction efficiency $\sim 84\%$. A 7 pixel grating operated at 1.1 THz with diffraction efficiency $\sim 80\%$ has also been realized in [26]. Recently, Mirzaei et al in [27] have pushed the frequency further to 1.4 THz, and even to the 4.7 THz with a 2×4 Fourier grating with a diffraction efficiency of 74% in [18]. A 4.7 THz grating of 2×4 will be used as an LO multiplexer for mapping [OI] line emission in Galactic/extragalactic Ultra long duration balloon Spectroscopic Stratospheric THz Observatory (GUSTO), which will be launched in 2021 [28]. Fourier gratings have good performance in terms of diffraction efficiency and uniformity among the image beams when the number of output beams is less than 10. In this case, about 20 – 30% of the incoming beam power is diffracted into unwanted higher diffraction order modes. Interestingly, a Fourier grating aiming for more diffraction orders (or a large number of diffracted beams) can offer a higher diffraction efficiency according to simulation shown below.

From the manufacturing point of view, accurately duplicating the surface profile of a Fourier grating is crucial [29], especially for large-pixel gratings working at supra-THz regions, since the performance of the grating is dominated by the surface profile. A Fourier grating operated at a higher frequency is more difficult to fabricate since the accuracy is more demanding. In this paper, we present a Fourier grating that generates 81 beams at 3.86 THz, where the incoming beam is provided by an unidirectional antenna coupled 3rd-order distributed feedback (DFB) QCL [30].

4.2 Fourier Grating

4.2.1 Diffraction theory

Based on the diffraction theory [31], the diffracted far field beam distribution from a phase grating is mathematically represented by

$$U(x, y) = \frac{e^{j\lambda z}}{j\lambda z} e^{j\frac{k}{2z}(x^2+y^2)} \iint_{-\infty}^{\infty} \left\{ U(\xi, \eta) e^{j\frac{k}{2z}(\xi^2+\eta^2)} \right\} e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)} d\xi d\eta, \quad (4.1)$$

where the term $U(\xi, \eta) \exp((jk/2z)(\xi^2 + \eta^2))$ describes the field distribution in the grating plane. Based on Eq. 4.1, the far field distribution is the Fourier transform of the field distribution in the grating plane. Since a phase grating manipulates the phase component of the incoming coherent beam, the field distribution in the phase grating plane is $\exp(j\Delta\phi(\xi, \eta))$, where $\Delta\phi(\xi, \eta)$ is called a phase modulation function and is expanded in a Fourier series with a set of Fourier coefficients a_n . Using the Fast Fourier Transform algorithm in Matlab, we define the far field multi-beams distribution. Then a set of a_n is found for the desired number of diffraction orders with high diffraction efficiency and good uniformity using the Standard multidimensional minimization algorithm in Matlab. According to the relation between phase difference and groove depth of the surface structure on the grating $d = \lambda\Delta\phi/4\pi\cos\theta_i$, where λ is the wavelength of the input radiation, $\Delta\phi$ the phase difference, and θ_i the incident angle with respect to the normal direction of the grating, we can define the groove profile of the grating based on the phase modulation function.

4.2.2 Grating design and fabrication

We generate a two-dimensional (2D) grating by superposition of two 1D gratings orthogonally. Thus its beam pattern is orthogonally distributed. In order to maintain the symmetry, gratings with an even number of employed diffraction-orders (pixels) are added with a half-wave phase step in one half of the unit cell to suppress all the even orders [25], making their surface structure

finer than odd-pixel gratings. Besides, even-pixel gratings have lower diffraction efficiency than odd-pixel gratings since the intensities in even diffraction-orders cannot be fully suppressed in most cases. Table 4.1 shows the diffraction efficiency of 1D gratings with different number of beams and their minimum radius of curvature (MRC) by assuming that the input beam is normally incident to the grating and by assuming a 1.2 mm unit cell. MRC is a crucial parameter for the manufacturer because the designed fine structure of the grating surface can only be reproduced when MRC of the grating is larger than the radius of the ball end mill used in a micro-milling machine. Our initial goal was to demonstrate a 100 beam grating. However, we chose to start with a grating for 81 beams because our simulation shows that a 9×9 pixel grating can achieve 98% diffraction efficiency and also a relatively uniform power distribution among the diffracted beams.

Table 4.1. The diffraction efficiency and minimum radius of curvature of gratings with different number of beams. All the gratings are illuminated with a normal incident beam and their unit cell sizes are fixed to 1.2 mm. Generally speaking, odd-pixel gratings have higher diffraction efficiency and larger MRC than what those from even-pixel gratings because even-pixel gratings are added a half-wave phase step in one half of the unit cell.

Pixel number	2	3	4	5	6
Diffraction efficiency(%)	80.6	92.5	90.8	92.3	86.6
MRC (μm)	102	1167	94	513	84
Pixel number	7	8	9	10	11
Diffraction efficiency(%)	96.9	91.9	99	87.0	97.5
MRC (μm)	312	62	267	54	153

Figure 4.1. (a) 81 pixel Fourier grating machined on a 5 mm thick aluminum plate. Gating contains 16×16 unit cells, each of them is $1.2 \text{ mm} \times 1.2 \text{ mm}$ in size, thus the entire grating is $2 \text{ cm} \times 2 \text{ cm}$. (b) The surface topology of the 81 pixel grating taken by a 3D optical microscope. The color indicates the height. (c), (d) The comparison between the designed profile in red (dashed) and the manufactured profile in blue.

Based on the equation for a 1D reflection grating, $D(\sin\theta_m - \sin\theta_i) = m\lambda$, where D is the periodicity, θ_m is the angle of the m 'th diffraction order, and θ_i is the incident angle with respect to the normal of the grating, the angular separation of the image beams is calculated to be $\sim 3.8^\circ$ (in our case, $D = 1.2 \text{ mm}$, $\theta_i = 12^\circ$, and $\lambda = 78 \text{ }\mu\text{m}$). The grating is machined on an aluminum plate (Alcoa QC-10 Mold Alloy, of 5 mm thick) using an KERN EVO micro-milling machine. The MRC for this design is $357 \text{ }\mu\text{m}$, which is about 4 times the radius ($90 \text{ }\mu\text{m}$) of the smallest ball end mill currently available for the micro-milling machine used. In this case, this machine is capable of patterning all the fine surface features. A photo of the manufactured grating and its 3D optical microscope image are shown in Figure 4.1 (a) and (b), respectively. The entire grating contains 16×16 unit cells and is $2 \text{ cm} \times 2 \text{ cm}$ in size. We also measured the surface profile of a unit cell in two orthogonal directions using a Dektak XT30 stylus profiler. We found good agreement between the measured profile and the designed one with a deviation less than $1 \text{ }\mu\text{m}$ in height ($1/78$ of the working wavelength). The effect of such a difference on the grating performance will be discussed in the results section.

4.3 Measurement setup

We apply an unidirectional antenna-coupled 3rd order distributed feedback (DFB) quantum cascade laser (QCL) at 3.86 THz as the input source for the grating. This laser can provide more than 10 mW output power. The unidirectionality, resulting from the reflector shown in Figure 4.2 (a), enhances the power level of the forward beam by a factor of ~ 2 . In our measurement, we used one of the lasers out of an array of 20 DFB lasers as the input source. Figure 4.2 (b) shows the laser array chip mounted on a carrier.

Figure 4.3 shows our measurement setup schematically. The QCL was mounted in a pulse tube cooler working at ~ 10 K. We measured the far field beam pattern of the laser at a distance of about 3.5 cm from the laser, which is shown in Figure 4.2 (c). The beam has a size ~ 25 mm in the vertical direction and ~ 15 mm in the horizontal direction, implying the full width at half-maximum (FWHM) divergence angles to be 23° and 14° in the vertical and horizontal directions, respectively. Obviously the beam has considerable deviation from a fundamental Gaussian beam profile. Since the Fourier grating duplicates the beam pattern of the input beam in its output, directly applying the beam in Figure 4.2 (c) to the grating requires a large distance to image the output beams with sufficient angular separation to be spatially resolved. However, taking into account the absorption by water vapor in the air at this frequency, we have to choose a short optical path that is within 30 cm in practice. To overcome this issue, we have to make a smaller and collimated incident beam to the grating. We introduced a high-density polyethylene plano-convex lens with a 20 mm focal length to collimate the QCL beam first and then we filtered it with a 5 mm iris aperture. The resulting beam is symmetric and Gaussian-like, shown in Figure 4.2 (d). This beam is nearly collimated with its FWHM divergence angle to be $< 1^\circ$. It is also important to notice that the incoming beam at the position of the grating has a diameter of 7 mm and covering more than 5 unit cells on the grating. Although the power of the modified beam is lower than the output power of the QCL (5-10% powers), there is still sufficient power to map output beams of the gratings with a good signal-to-noise ratio.

Figure 4.2. (a) The SEM of the 3rd-order DFB QCL [30]. (b) Array of DFB lasers gold-wire bonded to an electronic chip [30]. (c) Beam pattern of the QCL measured at a distance ~ 3.5 cm from the laser. It deviates from Gaussian profile and has large divergence angles in both vertical and horizontal directions. (d) Pattern of the QCL beam collimated by a lens and filtered by an iris aperture, measured after reflection from a flat gold-coated mirror in place of the grating in the setup.

The incident angles of the incoming beam are $12 \pm 2^\circ$ and $\pm 2^\circ$ with respect to the normal of the grating plane in the horizontal and vertical directions, respectively (see Figure 4.3). A pyro-electric room temperature detector mounted on a 2D scanner is used to map the image beam pattern at a distance of 12 cm from the grating surface. The detector has a 2-mm diameter aperture and is mounted inside an aluminum housing. The latter together with the planar mapping makes the measured power direction dependent with the maximum if the radiation is incident normally. The detector is read out by a lock-in amplifier. An arbitrary waveform generator is used to modulate the power supplier of the QCL and provides a reference to the lock-in amplifier with a 70 Hz sinusoidal function. A PC is used to control the 2D scanner and record the data from the lock-in amplifier.

To compare the total power of the image beams of the desired modes with that of the input beam, we measured the input beam power in the following way, where the grating is replaced by a gold coated mirror, which reflects nearly 100% power. The reflected single beam is also mapped by the pyro-electric detector at the same distance as measuring the grating imaging beam (12 cm). In this way, we can compare the relative power values accurately since the effect of water absorption due to the optical path is canceled out even though we do not know the absolute power. Caution has been taken to reduce stray light by introducing THz blackbody absorbers to cover the outside area of the circular aperture and the unilluminated area of the grating.

Figure 4.3. Schematic diagram of the measurement setup to test the performance of the grating. The QCL is cooled to ~ 10 K by a pulse tube cooler and its bias voltage is modulated by a sinusoidal function at 70 Hz using an arbitrary waveform generator. The QCL beam is first collimated by a high-density polyethylene lens and filtered by an iris aperture, then reflected by an aluminum mirror to illuminate the grating plane. A pyro-electric detector mounted on a 2D scanner stage is used to map the beam pattern. The received signal is read out by a lock-in amplifier with a 70 Hz sinusoidal function reference. The computer controls the stage and reads out the signal received from the lock-in amplifier.

4.4 Experiment results and discussions

Figure 4.4 (a) shows our measured beam pattern in a plane with an area of $84 \times 84 \text{ mm}^2$, at a distance of 120 mm from the grating surface. The intensity is expressed in units of voltage since the pyro-electric detector converts the

detected intensity to voltage. We observed 81 beams, which are well separated, and have angular directions matching to the 1D grating's equation. The angular separations for the output beams range from 3.8° to 4.1° , which agree well with the designed value of $\sim 3.8^\circ$. Some deviations from 3.8° comes from the fact that we recorded the beams at a plane, but a more appropriate way is to map the beams across a spherical surface since the diffracted beams propagate spherically in space. For the same reason, the measured beams show some distortions from a perfect rectangular beam distribution, which is mostly visible in the rightmost column of the beams. From the measured beam pattern, we found that the sizes of the output beams are almost the same as the input beam measured at the same distance (Figure 4.2 (d)), indicating the divergent angles of the output beams to be less than 1° . To visualize the power distribution of the diffracted beams, a 3D plot is also included in Figure 4.4 (b). We found that the power distribution in the vertical direction of the measured beams is slightly more uniform than the power distribution in the horizontal direction, except for the rightmost column, where the beams are both non-uniform and weaker. This is caused by the incident angle of 12° in the horizontal direction, but normal in the vertical direction.

To compare the measurement with the prediction, Figure 4.4 (d) shows the simulated diffracted beam pattern of the grating using COMSOL Multiphysics [32]. The result is simulated by importing the surface profile of the designed unit cell of the grating and by repeating it in both orthogonal directions, while taking the input as a Gaussian beam. The simulated far field beam pattern is also plotted along the plane, which has the same distance to the grating surface as in our experiment. We can clearly see 81 rectangularly distributed beams, similar to the measurement in Fig 4 (a). In other words, the simulated 81 beams well reproduce the measured 81 beams. The detailed comparison between measurement and simulation regarding to diffraction efficiency and power uniformity will be given later. It is worth mentioning that the simulation shows the diffracted individual beams have the same beam profile as the input beam. However, we notice that the uniformity of the simulated 81 beams is better than what is seen in the measurement, especially for the beams in the rightmost column. In this analysis, we applied COMSOL because the Fast Fourier Transform algorithm in Matlab used to generate the surface profile is not suitable for generating spatially distributed diffracted beams.

For the non-uniformity in the measured beams, there are a few practical factors in the measurement that can affect the uniformity in the beam distribution: (1) There were humidity changes in the laboratory during the beam mapping, which took roughly 20 hours. During this period, the relative humidity varies between 25% and 45%, which in turn changes the absorption and influences the image beam intensity distribution. (2) Power coupling between the pyro-electric

detector and the image beams. During the mapping of the image beams, the measured power is angle-dependent, with more power for the beams in the center, but less power for the outer beams. (3) There are possible errors to determine the exact incident angle. The grating is designed for an incident angle of 12° in one direction and 0° in the orthogonal direction. However, in our experiment, it is problematic to determine the incident angle since THz radiation is invisible. We estimate an error of $\pm 2^\circ$ on the incident angles, which can also influence the intensity distribution of the image beams. (4) Different distances between the grating and individual image beams. Since we scan the detector along a plane, the distance between the grating and scanning position for each beam varies and it is larger for the outer beams. A longer distance means more loss due to the air absorption. All these experimental errors can influence the measurement of the grating with regard to the diffraction efficiency and uniformity.

To correct the error due to the angle-dependent power measured by the pyro-electric detector, we calibrated the dependence by changing the facing angle of the detector to the beams in both vertical and horizontal directions. We then adjusted the measured intensity of the beams. We also measured the power loss due to different distances between the grating and individual image beams, and found a maximum loss of 0.8%, which is negligible. Other errors are difficult to correct so the only correction is the angular dependence of the detector power in our data analysis. However, we removed the noise floor caused by the pyro-electric detector itself in the image beam data and in the input beam data. Figure 4.4. (c) shows the corrected measured beam pattern, which agrees better with the simulated one in Figure 4.4 (d). We then calculated the diffraction efficiency based on the corrected data set. We found that the diffraction efficiency is $94 \pm 3\%$. This efficiency suggests that 94% of power has been transferred from the input beam to the diffracted 81 beams by the grating. Clearly, it is a highly efficient Fourier grating. The error bar accounts mainly for the following two sources: the humidity changes in the laboratory and the $\pm 2^\circ$ error in the incident angle.

In running COMSOL Multiphysics, we used the periodic port with periodic boundary conditions in the RF (radio frequency) module to get the simulated diffraction efficiency. The simulated diffraction efficiency of the designed grating is 98%, but as stated in section 3, there is a small mismatch ($\sim 1 \mu\text{m}$) between the manufactured and designed surface profile. So we also imported the manufactured surface profile into COMSOL and found a diffraction efficiency of 97%. It reduces the efficiency by 1%. This 97% value agrees with the measured value of $94 \pm 3\%$ within the margin of error.

Figure 4.4. (a) Measured beam pattern. (b) 3D beam profile of the image beam pattern. (c) Image beam pattern after calibrated the effect of the coupling with detector and removed the noise floor. (d) Simulated far field beam pattern of the designed grating.

Another important performance indicator of a grating is its uniformity in beam power distribution. When the grating is used to generate multiple beams as a local oscillator, each beam will pump a mixer, and thus the power should be within certain range of the desired value, in which all the mixers will perform optimally. The details can depend on the sensitivity of the mixers and the optical components before the mixer. In supra-THz region, superconducting hot electron bolometer (HEB) mixers are the detectors of choice for heterodyne instrumentation due to their high sensitivities and low LO power requirements. However, unlike superconducting-insulator-superconductor (SIS) mixers, which are operated only below 1.4 THz, and Schottky diode mixers, which are relatively insensitive to variation of the LO power, the performance of HEB mixers is LO power dependent [33]. Based on a set of pumped current-voltage characteristic data with a variable LO power in [34] and the isothermal technique [35], we find that if the LO power changes within $\pm 20\%$ around its optimal power, the receiver noise temperature, which characterizes the

sensitivity of a heterodyne receiver, remains at a value within 10% of the best sensitivity [36].

From the data in Figure 4.4 (c), we calculate the relative power for each beam, and plot them in different columns in Figure 4.5 (a), where we should expect all the beams to weight for 1.2 % of the total power if the diffracted beams are perfectly uniform.

Figure 4.5. (a) The power distribution of the measured image beams distributed in different columns. (b) The power distribution of the image beams from the simulation using a designed surface structure.

We found that the relative power varies from 0.4 to 1.5 % and the non-uniformity happens mainly on the two rightmost columns (columns 8 & 9) in the measured beam pattern. For comparison, the simulated power distribution is plotted in Figure 4.5 (b), where the relative power varies from 0.8 to 1.45 %. So the simulation gives a better uniformity. However, the simulation also suggests the non-uniformity contributed largely by the rightmost column. From Figure 4.5(a) the power of 64 beams out of 81 are within $\pm 20\%$ range. As an important characteristic for the coupling between the output beam and an HEB mixer, the Gaussities of these 64 beams are calculated by fitting them to a fundamental Gaussian beam expression. They vary in a range between 93%-96%, which is negligibly small. In other word, the 64 beams can be directly used to pump an uniform HEB mixer array, where every HEB requires the same LO power. In contrast, 78 beams out of 81 vary within this range from the simulation. The difference is likely due to the mismatch between the designed and the manufactured surface profile. By importing one unit cell of the manufactured surface topology into COMSOL Multiphysics and simulating the power distribution of the output beams, we find that 68 beams out of 81 are within $\pm 20\%$ around the nominal value. Therefore, the precision in manufacturing seems to play a crucial role in the uniformity of the grating. Besides, the humidity change

in the laboratory may also affect the uniformity. Despite the non-uniformity in the measured beams, we can still effectively use all 81 beams by replacing the detectors that require lower or higher LO than the nominal value instead of an ideal uniform HEB array. It is relatively easy to control the required LO power of a HEB mixer by controlling the size of an HEB.

To realize the simulated uniformity, we can improve the manufacturing accuracy, for example, to be as good as $0.5\ \mu\text{m}$. However, to improve the power uniformity of the LO array beyond the current simulation result, there are two possible methods to proceed. Firstly, one can design a 2D grating by directly searching for the Fourier coefficients for a 2D grating instead of superimposing two 1D gratings orthogonally. It has been recently shown that the diffraction efficiency is improved using this method [37]. Potentially it may improve the uniformity, but it needs to be demonstrated in practice. Alternatively, one can use two 1D gratings to generate a rectangularly distributed beam pattern. From the beam pattern in Figure 4.4, the power distribution in the vertical direction is obviously more uniform than that in the horizontal direction. That is due to the different incident angles in these two directions, being 0° in vertical direction and 12° in horizontal direction. Illuminating the grating with a normally incident beam will increase the uniformity of the grating, but in reality a non-zero incident angle is needed for a reflection grating. Since both the simulation and measurement results demonstrate that the incident angle in the horizontal direction has nearly no influence on the power uniformity in the vertical direction, one can generate 81 beams by using two separate 1D gratings of 9-pixels in series.

4.5 Conclusion

We report a 81-beams supra-THz LO array generated by a Fourier grating with a unidirectional 3rd-order DFB QCL emitting single mode radiation at 3.86 THz. We succeeded in measuring 81 diffraction beams and, due to a high output power of the QCL, we have achieved a good signal-to-noise ratio allowing us to determine the diffraction efficiency of the grating, which is $94\pm3\%$, and evaluate the power uniformity of the image beams. The measured diffraction efficiency agrees well with the simulated result using the profile of the manufactured Fourier grating. The latter gives 97% efficiency. Based on the measurements and uniformity requirement of the LO power for superconducting HEB mixers, we find 64 beams out of 81 have their power varying within $\pm 20\%$ around the nominal value and that the 64 beams can be used to pump a 64 uniform array, maintaining the sensitivity degraded less than 10%. Our results open a new route towards a large heterodyne array of order of 100 pixels for future space instruments. Our Fourier grating approach can improve the functionalities of

the phase gratings, such as the diffraction efficiency, for orbital angular momentum beams for optical communications, UV beam splitting, and complex beam shaping.

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measured a set of current-voltage curves of a similar HEB mixer pumped with different LO power operated at 4.3 THz, and from the data when the LO power varies within $\sim 40\%$ the change in HEB mixer's bias current is $\sim 37\%$, which responds to $\sim 10\%$ changes in the noise temperature.

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Chapter 5

Bandwidth of a 4.7 THz asymmetric Fourier grating

Based on

Y. Gan, B. Mirzaei, J. R. G. Silva, W. Laauwen, F.F.S. van der Tak, and J. R. Gao, the 30th International Symposium on Space Terahertz Technology (ISSTT,2019), Gothenburg, Sweden, 2019.

We present an analysis of the bandwidth of a preliminary designed asymmetric 8-pixel Fourier grating as the beam multiplexer for the 4.7 THz local oscillator of the GUSTO mission. We take the GUSTO grating as an example to address the bandwidth question although GUSTO itself does not need to operate over a wide frequency range. By illuminating single beams with different frequencies from 4.445 THz to 5.045 THz to the grating, we simulated the changes in the grating's performance in three aspects using COMSOL Multiphysics: diffraction efficiency, power distribution, and the angular distribution of the output beams. These parameters can reduce the coupling efficiency between the output beams of the grating and the beams of the mixer array of GUSTO. The grating's bandwidth is calculated to be 250 GHz, which is sufficient for many applications.

5.1 Introduction

Heterodyne detection is widely used to detect atomic fine structure lines and molecular rotational lines in the terahertz (THz) frequency region from the interstellar medium (ISM). This technique provides very high spectral resolution, $R > 10^6$. Heterodyne receivers convert a sky signal in THz down to gigahertz frequency by mixing the weak celestial signal with a signal from a local oscillator (LO). In the supra-THz region (> 1 THz), quantum cascade lasers (QCLs) provide considerably higher output powers compared to LO sources based on multipliers [1]. Therefore, the 4.745 THz band in the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO) [2], aiming for detection of [OI] line emission from the Milky Way and nearby galaxies, especially the Magellanic Clouds, combines a QCL and a Fourier grating as the LO for the 8-pixel hot electron bolometer (HEB) lens-antenna coupled mixer array. The array is crucial to enhance observation speed. In order to detect the Doppler shift caused by the linear velocity of the ISM beyond our galaxy, a sizable tuning range of LO will be necessary since the IF bandwidth of a HEB mixer available in this frequency range is limited. So, an interesting question is how large the bandwidth of a Fourier grating can be.

A Fourier grating as a multiplexer to diffract a single beam from the QCL to multiple beams is designed to work across a finite frequency range. For a given Fourier grating, the change of the source frequency causes a loss in the coupling efficiency between the image beams of the grating and the beams of the mixers [3]. So the bandwidth of a Fourier grating is characterized by the interplay between the grating and an array. Thus, the bandwidth analysis should take the specific array used into account. Figure 5.1 shows a conceptual diagram of the 4.745 THz array receiver. A single QCL beam is first diffracted to 8 beams by a reflective Fourier grating, which are collimated by a parabolic mirror, becoming parallel to each other. These 8 parallel beams are then coupled to the lens-antennas of the mixer array. We analyze the bandwidth of an 8-pixel Fourier grating designed for the 4.745 THz band of GUSTO, as an example. We notice that GUSTO itself does not require a large bandwidth since it aims to detect [OI] lines from the Milky Way. Furthermore, we took a GUSTO grating design available at the time when we performed the analysis, which is not the final one. We do believe that the approach we present here should be applicable for any combinations of a grating LO with an array.

Figure 5.1. Conceptual diagram of the 4.745 THz 8 beam local oscillator for the GUSTO mission. The QCL beam is first diffracted by a reflective phase grating, and is then collimated by a parabolic mirror to make the 8 parallel beams. These 8 beams are coupled to a quasi-optical mixer array.

5.2 Simulated 4.745 THz Fourier grating

A phase grating consists of a periodic structure to diffract a single beam to multi-beams in different directions through phase modulation. According to diffraction theory, the diffracted far field distribution from a grating can be expressed as the Fourier transform of the grating's transmission/reflection function [4]. Gratings using Fourier synthesis technique to achieve continuous phase-only groove shapes are called Fourier gratings [5]. To design a Fourier grating, we expanded the phase modulation function of the grating to Fourier series with a set of Fourier coefficients a_n . Using the Fast Fourier Transform and the Standard multidimensional minimization algorithm in Matlab, we found a set of a_n for a one-dimensional grating with the desired number of pixels. A two dimensional grating is generated by superimposing two 1D profiles orthogonally. In our case, one direction is a 2-pixel 1D grating, and the other direction is a 4-pixel 1D grating. According to the grating equation $D(\sin\theta_m - \sin\theta_i) = m \cdot \lambda$, the direction of the output beam θ_m in the diffraction order m (integer) is determined by the grating period D , the incident angle with respect to the normal of the grating θ_i and working wavelength λ . An asymmetric grating is designed to accommodate the requirements of the GUSTO optical system by employing consecutive diffraction orders [6]. For the 4-pixel 1D grating, we chose the $(-2, -1, 0, +1)$ diffraction orders, and for the 2-pixel 1D

grating, we chose the $(-1,0)$ diffraction orders. The surface topology and specifications (as simulated with COMSOL Multiphysics [7]) of the design are shown in Figure 5.2 and Table 5.1, respectively.

Figure 5.2. The surface topology of one unit cell of the grating [6]. The input QCL beam illuminates the grating surface with an incident angle 15° in the x direction and 0° in the y direction.

Table 5.1. Grating Specifications

Working frequency	4.745THz
Material	Aluminum
Angular distribution	1.83°
Incident angle	15°
Unit cell size	2.04mm×1.979mm
Diffraction orders	$(-1,0)(-2,-1,0,1)$
Diffraction efficiency	70.2%
Uniformity deviation = $(I_{max}-I_{min})/I_{average}$	12.5%

If the incident angle increases, the power variation among the output beams becomes larger [8]. The different unit cell size in two directions is to make the angular distribution in these two directions the same. The diffraction efficiency, defined as the ratio of the total diffracted beam power to the power of the incoming beam. The power variation is simulated by using COMSOL Multiphysics and by importing the surface topology of the grating. We apply the periodic port with periodic boundary condition in the RF module, and extract the S-parameters of the port. The power distribution of the output beams is plotted in Figure 5.3 (a), where we find the largest variation to be 12.5%

(between the maximum power and the minimum power). By importing the surface profile of the designed unit cell of the grating and by repeating it in both orthogonal directions, while taking the input as a Gaussian beam, we simulated the far field beam pattern of the grating. The outcome is shown in Figure 5.3 (b), where the m and n are the diffraction orders in both directions. From the results in Figure 5.3, we conclude that the grating achieves a good power uniformity among the output beams.

Figure 5.3. (a) Power distribution of the 8 output beams from the grating. The largest variation is 12.5% (between the maximum power and the minimum power). (b) Far field beam pattern of the grating. The m and n are the diffraction orders in two directions.

5.3 Calculation of the grating bandwidth

The 8 output beams from the grating are used to pump an 8-pixel mixer array in the 4.745 THz band of GUSTO. The power variation among the LO beams can degrade the sensitivity of the mixers in the array since it depends on LO power. We assume that the latter should be within 5% of the optimal value, and we also assume all HEBs in the array require the exact same LO power. The corresponding LO power variation is estimated to be $\sim 21\%$ using the isothermal technique [9,10,11]. In this paper, we use this criterion to define the bandwidth of the grating, namely, as the frequency range changes such that the LO power variation among the array mixers is within 21%.

The change of the frequency affects the performance of the grating in three aspects: (a) frequency change causes a change in the diffraction efficiency η ; (b) Frequency change causes a change in the power distribution of the outcome beams; (c) According to the grating equation, the frequency change affects also the angular distribution of the output beams, which reduces optical coupling to the lens-antennas of the mixer array.

Based on these three aspects, we defined Gaussian beams with different frequencies from 4.445 THz to 5.045 THz to illuminate the grating used in COMSOL Multiphysics. The simulation results, in which the changes in diffraction efficiency when the frequency of the beams is changed, are shown in Table 5.2.

Table 5.2. The diffraction efficiencies η corresponding to different frequencies f from 4.445THz to 5.045 THz

$f(\text{THz})$	4.445	4.545	4.645	4.745	4.845	4.845	5.045
η	70.6%	70.5%	70.4%	70.2%	70.0%	69.7%	69.4%

Table 5.2 suggests that the maximal change in diffraction efficiency by varying the frequency is 0.8%, which is negligible compared to other effects (the power distribution and the angular distribution).

Figure 5.4. Power distribution of the output beams when the working frequency changes from 4.445 THz to 5.045 THz. Red dashed lines indicate the LO power boundaries, within which the powers of the output beams vary within 21% around their average value.

When the frequency changes, the power distribution among the output beams varies. When the grating works at the nominal (or designed) frequency of 4.745

THz, its maximal power variation of the output beams is 12.5% (between the maximum power and the minimum power). When the frequency changes, this number becomes larger. Figure 5.4 plots the power distribution of the output beams of the grating operated at different frequencies. The red dashed lines indicate the LO power boundaries, within which the power of the output beams varies within 21% around their average value. From Figure 5.4, when the frequency changes between 4.575 THz and 4.825 THz, the relative powers of all the output beams from the grating vary within 21% around their average value (8.6%). Based on this we derive that the bandwidth of the grating is 250 GHz.

Now we examine the angular distribution of the output beams as a function of the frequency. Since the pixel spacing of the mixer array is fixed, the change in the spacing of the beams can lead to offsets with respect to those of the mixer array. According to the relation between the offset and Gaussian beam coupling [12], we can calculate the coupling loss caused by the offset at different frequencies. The results are shown in Figure 5.5.

Figure 5.5. The change of the coupling efficiency between the output beams and the mixer array caused by the spatial offset between them (or called misaligned).

Based on the grating equation, we calculated the angular distribution of the output beams and the offset between the output beams and the lens-antennas at different frequencies. Then, taking advantage of the offset dependence of coupling efficiency in Figure 5.5, we obtained the coupling loss caused by the offset. The next step is to calculate the distribution of powers that are effectively coupled to the mixer array. The results are shown in Figure 5.6.

Figure 5.6. Power distribution of the output beams, taking the angular distribution into consideration when the working frequency changes from 4.445 THz to 5.045 THz. Red dashed lines indicate the LO power boundaries, within which the powers of the output beams vary within 21% around their average value.

In Figure 5.6 the red dashed lines indicate the LO power boundaries, within which the powers of the output beams vary within 21%, where the average value is 8.5 %. We find that the coupled powers are still within 21% with frequency changing between 4.575 THz and 4.825 THz. Therefore, from this aspect, the bandwidth of the grating is also 250 GHz.

5.4 Conclusions

We analysed the bandwidth of an asymmetric grating preliminary designed for the 4.745 THz local oscillator for GUSTO in three aspects; diffraction efficiency, power distribution and angular distribution. We found that for a 4.745 THz asymmetric grating, its output beam power variation remains within 21% when the operating frequency changes from 4.575 THz to 4.825 THz, which gives a 250 GHz frequency bandwidth. The effect is dominated by the power distribution and angular distribution, while the diffraction efficiency remains nearly unchanged. The 250 GHz bandwidth corresponds to 15,000 km/s linear velocity,

which is much more than the line widths of the galactic (~ 100 km/s) and extragalactic (~ 1000 km/s) objects.

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Chapter 6

Heterodyne performance of an MgB_2 hot electron bolometer at 1.63 THz and 2.52 THz

Based on

Y. Gan, B. Mirzaei, J.R.G. Silva, J. Chang, S. Cherednichenko, F. van der Tak, and J.R. Gao, to be submitted to Journal of Applied Physics (2021).

We have fabricated spiral antenna coupled MgB_2 hot electron bolometer (HEB) mixers using a 5 nm thick MgB_2 film with a critical temperature of 33.9 K, where the bridge size is 0.4 μm in width and 1.2 μm in length. The heterodyne sensitivity was determined using the Y-factor technique. The lowest double sideband receiver noise temperature was measured to be 2590 K at 1.63 THz and 3290 K at 2.52 THz at 5 K bath temperature, operated with local oscillator power of about 13 μW at the HEB. At 1.63 THz, the sensitivity decreases by 15%, and 37% when the bath temperature increases to 15 K and 20 K, respectively. We also measured the noise bandwidth of 11 GHz of the device at 1.63 THz and at 5 K.

6.1 Introduction

Terahertz (THz) radiation from our galaxies and other galaxies is essential to understand the star formation process. Superconducting hot electron bolometers (HEB) based on niobium nitride (NbN) thin film are the most sensitive detectors above 1.5 THz so far. Ionized carbon [CII] and atomic oxygen [OI] fine structure lines, at 1.89 THz and 4.74 THz, respectively, are two of the most important lines in the THz region. With increasing the frequency, a larger IF bandwidth is required for the mixers to remain the same velocity resolution, e.g., the required IF bandwidth at 4.74 THz is 6 GHz, which is 2.5 times of that at 1.89 THz. The typical IF bandwidth for a NbN HEB mixer is 4 GHz, thus not enough to resolve the velocity information at the high end of terahertz frequencies. Superconducting MgB_2 is found to have a high critical temperature T_c (39 K in Bulk) and a shorter electron-phonon interaction time (1-2 ps). Therefore, the HBE based on MgB_2 thin film is able to enlarge the IF bandwidth.

The reported MgB_2 HEBs are based on the films grown by Molecular Beam Epitaxy (MBE) or Hybrid Physical Chemical Vapor Deposition (HPCVD). Table 6.1 summarizes the MgB_2 HEBs and their double sideband (DSB) receiver noise temperatures and bandwidths reported in the literature. In 2007, S. Cherednichenko et al. reported the first MgB_2 HEB, fabricated on a 20 nm MBE grown film with a $T_c = 22$ K, which resulted in an uncorrected DSB receiver noise temperature of 11000 K at 1.6 THz and a mixer gain bandwidth (GBW) of 2.3 GHz [1]. In 2015, D. Cunnane et al. reported the first MgB_2 HEB mixer based on 10-20 nm HPCVD grown films with a T_c of 33-38 K, which gives an uncorrected DSB receiver noise temperature of 3900 K at 600 GHz and an IF bandwidth of 6.9 GHz [4]. As suggested from Table 6.1, the MgB_2 films grown by HPCVD can achieve a higher T_c . An alternative way to realize the MgB_2 thin film with a high T_c is by an Ar ion mill from a thicker film [6]. In this case, the high T_c improves the IF bandwidth, but it increases the receiver noise temperature. A breakthrough of a low noise MgB_2 HEB is made by E. Novoselov and S. Cherednichenko in 2017 [8], who reported an MgB_2 HEB mixer based on 6 nm HPCVD grown film with a $T_c = 31$ K, which results in an uncorrected receiver noise temperature of 1160 K at 1.6 THz and a NBW of 11 GHz. Both were measured at 5 K.

Table 6.1. Summary of the reported MgB_2 HEBs. The table includes the film thickness t , the method to grow the MgB_2 film, the critical temperature of the device, and the reported receiver noise temperature T_{rec} and IF bandwidth f_{IF} . The operation temperature T_{bath} and frequency of the local oscillator (LO) f_{LO} are also given in the table. The superscript “corr.” in the T_{rec} means that this

number is the measured receiver noise temperature corrected for some optical losses.

Ref. year	t (nm)	Grown method	T_c (K)	T_{rec} (K)	f_{IF} (GHz)	T_{bath} (K)	f_{LO} (THz)
[1]. 2007	20	MBE	22	11000	2.3	4.2	1.6
[2]. 2015	10	MBE	8.5	700 ^{corr.}	2.2-3	4.2	0.6
[3]. 2016	20	MBE	22.5	1700 ^{corr.} 2150 ^{corr.}	5	4.2 12	1.6
[4]. 2015	10-20	HPCVD	33-38	3900	6.9	9	0.6
[5]. 2016	15	HPCVD	35	4300 ^{corr.}	6	23	0.69
[7]. 2017	7	HPCVD	34	2000 3600	6.5	8.2	0.6 1.9
[8]. 2017	6	HPCVD	31	930 ^{corr.} 1120 ^{corr.} 1630 ^{corr.}	11	5 15 20	1.6

In this work, we reported a MgB_2 HEB mixer fabricated on a 5 nm HPCVD thin film with a $T_c = 33.9$ K. The receiver noise temperatures of the HEB were measured with a 1.63 THz LO, at a bath temperature from 5 K to 20 K. The noise bandwidth (NBW) was also measured at 5 K and 20 K. Furthermore, the same HEB was characterized with a 2.52 THz LO at 5 K.

6.2 HEB device and measurement setup

The MgB_2 film used in our study is from Chalmers University of Technology and is fabricated using a HPCVD method. The detailed deposition process can be found in [9]. The thickness of the MgB_2 film is 5 nm according to the deposition rate. The substrate is a 320 μm thick SiC, which gives only a 0.42% lattice mismatch to the MgB_2 film [10]. The MgB_2 film is protected by an in-situ sputtered 20 nm thick Au layer. The HEB fabrication at TU Delft starts with the definition of the contact-pads with e-beam lithography (EBL) and Au evaporation in combination with a lift-off process. Then, the spiral antennas are defined using a similar process, but by evaporating a thicker Au layer together with a layer of Ti on the top. The latter is to prevent etching of the Au antenna during the Ar Ion beam milling etching (IBME) to define the MgB_2 bridge width. The Au protecting layer is then physically removed using IBME, followed by sputtering a 40 nm Si_3N_4 layer, which intends to prevent the oxidation of MgB_2 in the following fabrication step. The mask for the definition of the submicron-bridge is then patterned using EBL. Finally the uncovered Si_3N_4 and MgB_2 are physically etched away, where an MgB_2 submicron-bridge connecting the contact pads is formed and the device is thus completed.

Figure 6.1 shows the SEM image of a completed MgB_2 HEB, together with a 3D drawing of the MgB_2 bridge and the contact pads. The MgB_2 bridge has $0.4\ \mu\text{m}$ width and $1.2\ \mu\text{m}$ length and has a room temperature resistance of $84\ \Omega$. The low temperature normal-state resistance (R_N) above the T_c is $62\ \Omega$, which is assumed to be the same as the HEB impedance at the THz frequency. This value is slightly lower than the required resistance of $80\ \Omega$ of the spiral antenna used. The residual resistance ratio ($\text{RRR} = R_{295\text{K}}/R_{5\text{K}}$) of the HEB is found to be 1.35. The MgB_2 HEB has a critical temperature of 33.9 K, and a critical current of 0.9 mA at 5 K, giving a critical current density of $4.5 \times 10^7\ \text{A}/\text{cm}^2$.

However, we found an increase of the room temperature resistance of the device from $84\ \Omega$ to $108\ \Omega$ after it was exposed to the air and a moisture environment. The R_N and the critical current are also changed and become $78\ \Omega$ and 0.68 mA, respectively. Since the MgB_2 is known to be sensitive to water, our Si_3N_4 layer in terms of the thickness and width is not sufficient to protect the MgB_2 .

Figure 6.1. SEM micrograph of a spiral antenna coupled MgB_2 HEB, fabricated at TU Delft. The inset is a 3D model of the MgB_2 submicron-bridge and part of the contact pads and spiral antenna. Different colors are used to indicate different materials.

Figure 6.2 shows the schematic of the experimental setup for measuring the DSB receiver noise temperature ($T_{\text{rec}}^{\text{DSB}}$) of MgB_2 HEBs. The method is the Y-factor technique [11] using THz calibration sources of 293 K (hot)/77 K (cold) blackbody loads. A far-infrared gas laser, optically pumped by a CO_2 laser, acts as a local oscillator (LO), and can emit lines at a different frequency by combining a specific gas with a CO_2 pumping line. A voice coil attenuator together with a proportional–integral–derivative (PID) feed-back loop is used to

stabilize the LO power absorbed by the HEB. The T_{rec}^{DSB} of this device is measured at 1.63 THz and 2.52 THz, respectively. The signal and the LO are combined by a 6 μm Mylar beam splitter, passing through an ultra-high-molecular-weight polyethylene (UHMW-PE) window at 300 K and a metal-mesh heat filter at 4 K, then reaching the Si lens coupled HEB. The HEB is glued on the back side of an elliptical Si lens [12] with an anti-reflection coating. The coating material is Parylene C and the thickness is 28 μm , which is designed for 1.63 THz. The lens-antenna HEB mixer is mounted in a metal block, which is anchored on the 4 K plate of a L-He cryostat. Their interface is on purpose made thermally resistive so that the operating temperature can be raised. A heater together with a temperature sensor is installed on the mixer block to elevate the local temperature of the mixer from the bath temperature up to the T_c . The optical losses contained in the optical path are presented in Table 6.2, where the optical loss of the coated Si lens is simulated using COMSOL Multiphysics, taking the absorption coefficients of Parylene C of 10.5 cm^{-1} at 1.63 THz and 16.2 cm^{-1} at 2.52 THz into consideration [13,14].

A 0.2-18 GHz cryogenic Bias-Tee is used to give DC bias to the HEB and transmit the intermediate frequency (IF) to the amplifier chain. The latter includes a 0.1-14 GHz cryogenic Low Noise Amplifier (LNA) with a 39 dB gain, a 0.1-14 GHz room temperature (RT) LNA with a 42 dB gain, and a 0.1-12 GHz RT LNA with a 30 dB gain. A bandpass filter with 100 MHz bandwidth is used to filter the IF signal at 2 GHz. Between each two elements there are attenuator(s) to minimize the standing waves, and the total gain of the IF chain is 84 dB (at 2 GHz), and the noise temperature contribution from the IF chain to the mixer is 4.5 K at 2 GHz. The amplified IF signal is read out by a power meter.

To measure the IF bandwidth of the HEB, the bandpass filter and second RT LNA are removed from the setup. Also the power meter is replaced by a spectrum analyzer, which records the receiver output power versus IF in response to the hot load and cold load. Then, the receiver noise temperature vs IF can be obtained by applying again the Y-factor technique.

Figure 6.2. Measurement setup for DSB receiver noise temperatures of the MgB_2 HEB mixer

Table 6.2. Loss of the components in the optical path from the hot/cold loads to the HEB, including the 30 cm air path (L_{air}), the 6 μm Mylar beam splitter (L_{BS}) at 300 K, the window (L_{window}) at 300K, the heat filter (L_{filter}) at 4 K, the coated Si lens (L_{lens}) at 4K, and the coupling between antenna and HEB. The measured $T_{\text{rec}}^{\text{DSB}}$ at two frequencies are also presented.

Frequency	L_{air} (dB)	L_{BS} (dB)	L_{window} (dB)	L_{filter} (dB)	L_{lens} (dB)	L_{coupling} (dB)	$T_{\text{rec}}^{\text{DSB}}$ (K)
1.63 THz	0.65	0.27	0.43	0.90	0.35	0.35	2590
2.52 THz	0.38	0.56	0.61	0.73	1.11	0.54	3290

6.3 Measurement results

At the operating temperature of 5 K and with the LO at 1.63 THz, a set of IV curves from zero to fully pumped is measured and shown in Figure 6.3. Within the optimal operating region, which refers to 6-10 mV and 0.27-0.33 mA, the sensitivity of the HEB increases only 5% from its optimal value. The optimal LO power for the HEB is 13.6 μW at 1.63 THz, and 12.7 μW at 2.52 THz (to be described later). The LO power was determined by the standard Isothermal technique [15].

Figure 6.3. Current-voltage curves of the MgB_2 HEB mixer at different 1.63 THz LO power at 5 K operating temperature. At the optimal operating point, the required LO power is 13.6 μW . The yellow circle indicates the optimal operating region for this device at 1.63 THz derived from Figure 6.4. The IV curve with 2.52 THz LO optimal pumped is also plotted and the required LO power is calculated to be 12.7 μW .

To obtain the T_{rec}^{DSB} , we measured the receiver output power when the HEB is radiated by the hot load (P_{hot}) and the cold load (P_{cold}), respectively. To find the minimum T_{rec}^{DSB} , we scan the receiver output power versus HEB current at a number of bias voltages. The change of the HEB current is achieved by using the voice coil attenuator to vary the LO power at the HEB [11]. The advantage of this method is that the T_{rec}^{DSB} is not influenced by the fluctuations of the LO power and also the direct detection effect. The latter has no influence on the MgB_2 HEB since it requires much more LO power than for an NbN HEB [16]. The results are shown in Figure 6.4 (a) and (b), where the P_{hot} and P_{cold} are plotted as a function of the current at different bias voltages. Figure 6.4 (c) shows the T_{rec}^{DSB} versus current at different bias voltages, which are calculated using the Y-factor and also using the polynomial fitted curves to the data points from (a) and (b). Figure 6.4 (d) plots the minimum T_{rec}^{DSB} at each bias voltage. The inset of the same figure shows the minimum T_{rec}^{DSB} at different operating temperatures from 5 to 10 K. The lowest T_{rec}^{DSB} is found to be 2590 K at a bias voltage of 8 mV and a bias current of 0.3 mA. When the operating temperature increases, the T_{rec}^{DSB} stays nearly the

same from 5 K to 10 K, but increases by 15% when it is at 15 K and 37% at 20 K, respectively.

Figure 6.4. (a) (b) Measured receiver output power responding to hot and cold load as a function of the current of the HEB at different bias voltage from 2 mV to 14 mV at 1.63 THz and 5 K operating temperature. The solid lines are the polynomial fitted curves. (c) The calculated $T_{\text{rec}}^{\text{DSB}}$ as a function of the current of HEB using Y factor based on the fitted curves from (a) (b). (d) The minimum $T_{\text{rec}}^{\text{DSB}}$ at different bias voltages. The best bias voltage of this HEB is 8 mV. The inset is the $T_{\text{rec}}^{\text{DSB}}$ at different operation temperatures.

We also measured the P_{hot} and P_{cold} as a function of the bias voltage under the optimally pumped LO power. The results are plotted in Figure 6.5, where the P_{hot} and P_{cold} have shown clear structures that are also present in the resulted $T_{\text{rec}}^{\text{DSB}}$. The latter is plotted in the same figure in the green curve. They are reproducible, but the details are not, that is attributed to the fluctuations of the LO power from the FIR gas laser. For this particular measurement as a function of the bias voltage, we are not able to stabilize the LO power. Such structures have also been observed from other MgB_2 HEBs in the same batch and also the device from a different batch using a different film. The structures are new if we compare to the well understood NbN HEBs [11] or the MgB_2 HEB published in [8]. The reasons for the structures are unclear yet. It might be an interplay

between the submicron sized bridge and the inhomogeneity or defects in the film. The low RRR of 1.35 found in our HEB might support the hypothesis in [9].

The T_{rec}^{DSB} plotted as a function of the bias voltage shows the minimum T_{rec}^{DSB} of 2070 K at 8 mV. That this value is lower than what found in Figure 6.4 (c) is caused by the LO power variation between the measured hot and cold power curve.

Figure 6.5. Measured receiver output power (left axis) responding to the hot and cold load and resulted T_{rec}^{DSB} (right axis) as a function of the bias voltage with the HEB pumped at the optimal LO power at 1.63 THz and at 5 K operation temperature. Solid lines for the receiver output power are smoothed curves.

We also measured the T_{rec}^{DSB} of the same HEB with the LO at 2.5 THz. Using the same current scan method, we obtained the minimum T_{rec}^{DSB} to be 3290 K at 8 mV and 0.31 mA. The details are illustrated in Figure 6.6. By increasing the frequency to 2.52 THz, the optical losses in the optical path are also changed, as shown in Table 6.2. The minimum T_{rec}^{DSB} measured at 2.5 THz is 27 % higher than the one at 1.6 THz, that can be reasonably explained by the higher optical loss at 2.5 THz since the difference is 0.98 dB, which causes $\sim 25\%$ increase in T_{rec}^{DSB} . It is worth to mention that this is the first measured T_{rec}^{DSB} data at 2.5 THz reported for MgB_2 HEBs so far.

The consistency of the sensitivity observed between 1.6 and 2.5 THz does not provide any sign of the presence of the two superconducting gaps in MgB_2 [17]. With the measured T_c of 33.9 K in our device, the superconducting gaps of π -band and σ -band in the MgB_2 correspond to the gap frequency of 0.9 THz and 2.8 THz since $2\Delta_\pi = hf_\pi = 1.3k_B T_c$ and $2\Delta_\sigma = hf_\sigma = 4k_B T_c$ [18], respectively.

The k_B is the Boltzmann constant and the h is Planck constant. One might expect that the 2.5 THz data should behave differently than the data at 1.6 THz because it is higher than 0.9 THz and is also close to the 2.8 THz although no one has made a detailed prediction on the heterodyne performance yet. On the other hand, when the optimized pumped IV at 2.5 THz is plotted together with the one at 1.6 THz in Figure 6.3, we found they are almost identical. Thus, no signature of the two gaps seems to be present in our data.

Figure 6.6. Receiver output power (left axis) and the resulted T_{rec}^{DSB} (right axis) as function of the current of the HEB at 5 K and at 2.52 THz. The solid lines are polynomial fitted curves. The minimum noise temperature is 3290 K at 0.31 mA.

The IF noise bandwidth (NBW) of this device was measured at 5 K and 20 K at 1.63 THz. We first measured the P_{hot} and P_{cold} in the IF range of 0.2-14 GHz when the HEB is biased at the optimal point. Then using the Y-factor technique, the T_{rec}^{DSB} is plotted as a function of the IF in Figure 6.7. We used the equation $T_{rec}(f) = T_0(1 + (f/f_n)^2)$ to fit the T_{rec}^{DSB} vs IF data. For the data taken at 5 K we have the best fit when the NBW is 11 GHz, and for the data at 20 K, the NBW is 9.5 ± 1 GHz, where the large error bar is due to the low signal to noise ratio. Our NBW data support the result reported in [8]. However, in contrast to [8], where it was from 1 to 9 GHz, we performed the first NBW measurement for a MgB_2 HEB in the wide frequency range between 0.2-14 GHz.

The unexpected peak at 8 GHz is observed at different temperatures, different operating points, different LO frequencies, and also different HEBs. It seems to come from the IF chain. However, we characterized each component in the IF chain separately, we have not observed this particular feature around 8 GHz. We plan to measure the transmission of the IF chain by replacing the HEB with a 50

Ω resistor. Fortunately, this peak has little effect on our determination of the NBW.

Figure 6.7. T_{rec}^{DSB} as a function of the IF frequency at 5 K and 20 K. The solid lines are fitted use equation $T_{rec}(f) = T_0(1 + (f/f_n)^2)$, and the fitted noise bandwidth f_n is 11 GHz at 5 K and 9.5 GHz at 20 K with an error bar of ± 1 GHz.

6.4 Discussion

The measured receiver noise temperature of 2590 K at 1.63 THz is promising and is better than other MgB_2 HEBs reported in the literature [4-7] although it is higher than the best MgB_2 HEB in [8]. It is about three times the receiver noise temperature found in a NbN HEB (940 K) by assuming a similar optical loss [19]. The higher noise temperature due to the high T_c is expected because the output noise is proportional to it [20]. However, the mixer conversion gain might be different from the NbN HEB and is expected to be higher. To measure the gain, we did a dedicated measurement by using the U-factor [21]. Unfortunately, in our IF chain with a wide band, there are strong standing waves in the IF chain, more likely between the HEB and the first cryogenic LNA, the U-factor data are not reliable. Thus we are not able to perform a further analysis. Because of this, we have introduced a circulator at 1.7 GHz between HEB and LNA for a 5.3 THz MgB_2 HEB measurement to be described in Chapter 7.

The receiver noise temperature increases by 37% when the mixer operating temperature increases from 5 to 20 K. Interestingly, between 5 and 10 K, the sensitivity is nearly temperature independent. So, the MgB_2 HEB has the advantage of operating at different temperatures because of the higher T_c .

Therefore, an interesting question is that whether a MgB₂ HEB with even higher T_c (close to the $T_c = 39$ K in bulk) can achieve a low receiver noise temperature at ≥ 20 K. This particular temperature is attractive for space applications because there are compact, low mass, low dissipation, and space qualified Stirling coolers available [22].

The MgB₂ HEB mixer reported here comes from the very first batch fabricated at TU Delft. Apart from mitigating the issue of the MgB₂ bridge affected by the water vapor in air, we have a number of fabrication steps, which can be optimized and improved. One of them is to clean all the interfaces between layers during the fabrication. For example, our Au contact layer to the 20 nm Au protection layer (From Chalmers) will be sputter cleaned.

6.5 Conclusion

We have fabricated spiral antenna coupled MgB₂ hot electron bolometer (HEB) mixers based on a thin MgB₂ film. We measured the DSB receiver noise temperature of 2590 K at 1.63 THz and 3290 K at 2.52 THz. The latter was the first noise data at this frequency for the MgB₂ HEB in the literature. They are measured at 5 K operating temperature, with local oscillator power of 13 μ W at the HEB. The sensitivity at 1.6 THz decreases only by 37% when the operating temperature increases to 20 K, suggesting a high operating temperature above 20 K. We also built an IF bandwidth measurement setup, allowing for a frequency range between 0.2 and 14 GHz and measured the noise bandwidth of 11 GHz of the device.

We also found that the unprotected MgB₂ HEB is sensitive to the water vapor in air, which changes the room temperature resistance of the HEB. So, a protection layer to fully cover the HEB is essential.

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Chapter 7

Low noise MgB_2 hot electron bolometer mixer operated at 5.3 THz and at 20 K

Based on

Y. Gan, B. Mirzaei, J.R.G. Silva, J. Chang, S. Cherednichenko, F. van der Tak, and J.R. Gao, accepted by Applied Physics Letter (2021).

We have demonstrated a low noise superconducting MgB_2 hot electron bolometer (HEB) mixer working at the frequency of 5.3 terahertz (THz) with 20 K operation temperature. The bolometer consists of a 7 nm thick MgB_2 submicron-bridge contacted with a spiral antenna to couple THz radiation through a high resistive Si lens, and it has a superconducting critical temperature of 38.4 K. By using hot/cold blackbody loads and a Mylar beam splitter all in vacuum, and applying a 5.25 THz far-Infrared gas laser as local oscillator, we measured a minimal double sideband receiver noise temperature of 3960 K at the LO power of 9.5 μW . This can be further reduced to 2920 K if a Si lens with an antireflection coating optimized at this frequency and a 3 μm beam splitter are used. The measured intermediate frequency (IF) noise bandwidth is 9.5 GHz. The low noise, wide IF bandwidth mixers, which can be operated in a compact, low dissipation Stirling cooler, are more suitable for space applications than the existing HEB mixers. Furthermore, we likely observed a signature of the double-gap in the MgB_2 by comparing current-voltage curves pumped at 5.3 THz and 1.6 THz.

7.1 Introduction

Superconducting hot electron bolometer (HEB) mixers [1] are so far the most sensitive heterodyne detectors for high-resolution spectroscopy at frequencies between 1.2 and 6 THz [2]. They play a key role in astrophysics at terahertz (THz) frequencies, as this range is rich in the atomic, ionic, and molecular spectral lines that can, for example, directly probe how star formation proceeds in galaxies [3]. Such mixers have been successfully applied for the airborne telescope of Stratospheric Observatory for Infrared Astronomy [4], the balloon-borne telescope of Stratospheric Terahertz Observatory 2 [5], and the space telescope of the Herschel Space Observatory [6].

To date, HEB mixers based on thin NbN films have shown excellent sensitivities where their double sideband receiver noise temperature (T_{rec}^{DSB}) is approaching seven times the quantum noise [7]. However, one drawback of such mixers is their limited intermediate frequency (IF) bandwidth, typically below 4 GHz. Another restriction comes from the low operating temperature around 4 K due to their low critical temperature (T_c) of 8-10 K. Cooling down to 4 K, either by using Liquid He vessels or a mechanical pulse tube, is suboptimal for a space observatory considering the constraints on mass, volume, electrical power, and cost. For example, for the next generation of THz observatories with a number of telescopes operated as an interferometer in space [8] and the Earth atmospheric observations from space [9], the weight and consumed electrical power of cryo-coolers becomes much less if the operating temperature could be tolerated to 20 K or above.

Superconducting MgB_2 with a T_c of 40 K in bulk [10] is considered as a candidate to increase the IF bandwidth of an HEB mixer and also the operating temperature. The first MgB_2 HEB mixer based on a Molecular Beam Epitaxy (MBE) growth, 20 nm thick film with a T_c of 22 K was reported at 1.6 THz [11]. The HEB mixers based on Hybrid Physical Chemical Vapor Deposition (HPCVD) growth MgB_2 films, 10-20 nm, with an increased T_c of 33-38 K were reported at 600 GHz [12]. An HEB mixer based on a MgB_2 film of 7 nm with a T_c of 34 K, milled from a thicker film by an Ar ion mill, was measured at 600 GHz and 1.9 THz, with a T_{rec}^{DSB} of 3600 K at 1.9 THz and an IF noise bandwidth (NBW) of 6.5 GHz [13]. A combination of both a low T_{rec}^{DSB} of 930 K at 1.6 THz and a high NBW of 11 GHz in an MgB_2 HEB mixer at 5 K was reported in [14], which was based on an HPCVD, 5 nm film with a T_c of 31 K. The T_{rec}^{DSB} of this mixer increases by 75 % at 20 K. A similar T_{rec}^{DSB} (1000 K) at 1.6 THz together with a NBW of 13 GHz was achieved in [15]. The results in [13-15] raise the interesting question of whether it is suitable for the operation at 20 K, a temperature which is attractive

for space applications because of the availability of the compact, low mass, low dissipation, and space qualified Stirling coolers [16].

MgB_2 HEB mixers are thus the alternative to detect, for example, the astrophysically important molecular Hydrogen deuteride [HD] line at 2.67 and neutral atomic oxygen [OI] line at 4.75 THz, which can only be observed from space. However, until now, no sensitivity of such mixers at the frequencies above 1.9 THz has been reported. Importance of both experimental and theoretical studies at high frequencies (hence, photon energies) is also motivated by the fact that MgB_2 is known to have two families of conduction bands with distinct superconducting gaps [17], π -band Δ_π and σ -band Δ_σ . It has rather weakly interacting electrons. Photon assisted Cooper pair breaking is an essential part in HEB mixer operation, yet current mixing experimental data with ultra-thin MgB_2 (which can be assessed through HEB performance evaluation) is limited to <2 THz. This is still below the high-gap (σ -) frequency of MgB_2 . The question of the σ -band's role in THz detection/mixing remains open, yet scientifically interesting.

In this letter, we study an MgB_2 HEB mixer operated at 5.3 THz, which is well above the high-gap frequency. Furthermore, we intentionally increase the T_c of our MgB_2 film to 38.4 K [18] by increasing the thickness from 5 nm in [14] to 7 nm, i.e. close to its maximum theoretical value. The MgB_2 HEBs were fabricated as submicron-bridges integrated with a spiral antenna. Our experiment focuses at T_{rec}^{DSB} at 20 K, but the mixer noise temperature (T_m^{DSB}), conversion gain (G_m^{DSB}), and output noise (T_{out}) have also been measured from 6 K up to 23 K in order to fully characterize such a new mixer. In addition, the IF noise bandwidth was measured in the frequency range between 0.2-14 GHz to characterize it directly at 5.3 THz LO and 20 K.

7.2 HEB device and measurement setup

The HEB used, as shown in the inset (a) of Figure 7.1, consists of a 285 nm wide, 850 nm long, and 7 nm thick MgB_2 bridge on a 0.32 mm thick SiC substrate. The narrow bridge is to minimize the HEB volume and hence to reduce the required LO power. The narrow HEB may have a high noise temperature, but it can be operated with an existing FIR gas laser in the lab. The bridge is connected to a planar spiral antenna consisting of a 195 nm thick Au layer through contact-pads made of an Au layer with a thickness of ≥ 60 nm. The taped contact-pads are designed to reduce the reactance [19]. The antenna is designed to match the HEB impedance of 80Ω with an upper cutoff frequency of ≥ 6 THz [20]. Details of the fabrication of the HEB are described in the supplementary material.

The HEB used (#MgB2_BM3_2b) has a normal-state resistance of $51 \, \Omega$ (defined by the films sheet resistance and the bridge aspect ratio) at above its T_c , which is also the impedance at 5.3 THz [21]. The HEB has a T_c of 38.4 K and a critical current of 1.3 mA at 5 K, corresponding to a current density of $6.5 \times 10^7 \, \text{A/cm}^2$, which is a factor of 3 higher than what was reported in [14].

Figure 7.1. A set of current-voltage (IV) curves of a MgB_2 HEB mixer at 20 K by varying a 5.3 THz LO from zero to fully pumped to nearly normal state. The yellow circle indicates the optimal operating region for the lowest receiver noise temperature ($\leq 5\%$). At this optimal IV, the required LO power is $9.5 \, \mu\text{W}$. Inset (a) is an artistic impression of the HEB, which has the exactly same layout as the design; Inset (b) shows a comparison of the pumped IV curves with the same LO power at 1.6 THz and 5.3 THz, which are measured at 5 K and 20 K, respectively.

Figure 7.2 shows the schematic of our heterodyne measurement setups for measuring the $T_{\text{rec}}^{\text{DSB}}$ and G_m^{DSB} in (a) and for measuring IF NBW in (b). The LO is the far-Infrared (FIR) gas laser at 5.25 THz and the vacuum setup [22] is to avoid the high air absorption loss at 5.25 THz. A heater is installed on the mixer block to elevate the local temperature of the mixer. The components in the IF chain in (b) have a wide bandwidth (up to 14 GHz) to measure the IF NBW of the device. The detailed description of the measurement setups can be found in the supplementary material.

Figure 7.2. Schematics of the measurement setups for measuring the T_{rec}^{DSB} and G_m^{DSB} at 1.7 GHz in (a) and for measuring IF noise bandwidth in (b). The hot/cold loads and the Mylar beam splitter are placed in a vacuum enclosure, attached to the cryostat. A rotating mirror is used to switch between hot and cold loads. The 5.8 THz multimesh low pass filter functions as a heat filter.

Table 7.1 summarizes the optical loss ($1/G_{opt}$) at 5.25 THz in the optical path from the hot/cold loads to the HEB, which includes the Mylar beam splitter (BS), the multimesh low pass filter with a cut-off frequency of 5.8 THz acting as a heat filter, the Si lens, and the power coupling from antenna to HEB. The Si lens used [23] has an anti-reflection (AR) coating, but designed for 1.6 THz. The optical loss of the AR coated Si lens is simulated using COMSOL Multiphysics by taking the absorption coefficients of Parylene-C of 27 cm^{-1} at 5.25 THz into consideration [24,25]. The power loss from antenna to HEB is found to be 0.94 dB due to the lower HEB impedance ($51 \text{ } \Omega$) and is 0.31 dB more than the matched case [20].

Table 7.1. Loss of the components in the optical path from the hot/cold loads to the HEB at 5.25 THz, including the Mylar beam splitter (BS) (L_{BS}) at 300 K, the multimesh low pass filter (L_{filter}) at 4 K, the coated Si lens (L_{lens}) at 4 K, and the coupling between antenna and HEB. The measured T_{rec}^{DSB} together with an expected one if two components are optimized.

	L_{BS} (dB)	L_{filter} (dB)	L_{lens} (dB)	L_{coup} (dB)	T_{rec}^{DSB} (K)
6 μm BS & unoptimized coated lens	1.4	0.81	0.92	0.94	3960
3 μm BS & optimized coated lens	0.71	0.81	0.32	0.94	2920 (Estimated)

7.3 Measurement results

Figure 7.1 shows a set of IV curves of the HEB from zero to fully pumped by the 5.3 THz LO, recorded at 20 K. Within the optimal operating region (2.5-4 mV and 0.19-0.25 mA), the T_{rec}^{DSB} of the HEB, to be described, only increases by $\sim 5\%$ from its lowest value. From the optimally pumped IV we derive the LO power of 9.5 μW at the HEB using the Isothermal technique [26], implying a power of ≤ 0.5 mW from the FIR laser. Such a power can be provided by THz quantum cascade lasers, e.g. 50 mW in [27].

The T_{rec}^{DSB} of the mixer is obtained by using the Y-factor technique. The receiver output powers responding to the hot (P_{hot}) and cold loads (P_{cold}) are measured, and the ratio between these two is the Y-factor. Combining the Y-factor and the Callen-Welton temperatures of the blackbody loads, a T_{rec}^{DSB} can be obtained [22]. The P_{hot} and P_{cold} are scanned as a function of HEB current at different DC biased voltages, where the current reflects the scan of LO power by the voice coil attenuator. In this way, the T_{rec}^{DSB} is not influenced by the fluctuations of the LO power and by the direct detection effect [2, 22]. The latter is negligible in our case because the required LO power (9.5 μW) is three orders of magnitude higher than the RF power (~ 10 nW) that is the difference between the hot and cold loads. This is confirmed by the fact that we have not seen any shifts in pumped IV curves when the HEB faces two loads. Figure 7.3 plots the P_{hot} and P_{cold} as a function of current at the fixed bias voltage of 2.5 mV, measured at 20 K, and their polynomial fitted curves. The latter are used to determine the T_{rec}^{DSB} , plotted in the same figure, from which we select the minimum T_{rec}^{DSB} . We have carried out such measurements at a number of bias voltages ranging from 1 to 7 mV to obtain the minimum T_{rec}^{DSB} at each bias voltage. The results are summarized in the inset of Figure 7.3. The lowest T_{rec}^{DSB} is 3960 K when the HEB is biased at 2.5 mV and 0.21 mA.

The T_{rec}^{DSB} can be broken down to its constituents with the following expression [2]:

$$T_{rec}^{DSB} = T_{opt} + \frac{T_m^{DSB}}{G_{opt}} + \frac{T_{IF}}{G_{opt}G_m^{DSB}}, \quad (1)$$

$$T_m^{DSB} = \frac{T_{out}}{G_m^{DSB}}, \quad (2)$$

where T_{opt} is the noise temperature contribution of the optics ($= 137 \text{ K}$) and T_{IF} the noise temperature of the IF chain ($= 4.7 \text{ K}$). For simplicity, the contribution of the quantum noise is not included [28]. Furthermore, the T_m^{DSB} is determined by T_{out} and G_m^{DSB} through Eq. 2.

The measured T_{rec}^{DSB} could be improved to 2920 K if we would apply a Si lens with an AR coating optimized for 5.3 THz and utilize a thinner beam splitter of $3 \mu\text{m}$. The detailed reduction of optical loss can be found in Table 7.1, which includes also both measured and expected T_{rec}^{DSB} .

Figure 7.3. Measured receiver output power (left axis) of the MgB_2 HEB in response to hot/cold loads, together with the polynomial fits (in a solid line) as a function of the current and the resulted receiver noise temperature (right axis) when it is operated with an LO at 5.3 THz and at 20 K, and biased at 2.5 mV. The lowest noise temperature is 3960 K. The inset shows the minimum receiver noise temperature from such measurements for different bias voltages, varying from 1 to 7 mV.

At the optimal operating point (with the lowest T_{rec}^{DSB}), the receiver conversion gain ($G_{rec}^{DSB} = G_{opt} G_m^{DSB}$) is measured by using the U-factor [29], which is the ratio between the receiver output power when the HEB is in its operating point and the receiver output power when it is in its superconducting state. The G_m^{DSB} is -7.6 dB by subtracting all the optical losses from the G_{rec}^{DSB} based on the measured U-factor of 14.3 dB. The T_m^{DSB} is 1470 K and the T_{out} is 250 K using Eqs. 1&2. We note that the circulator in our setup is crucial to obtain the reliable U-factor because it prevents the standing waves (see Figure 7.5(a)) between the HEB and the low noise amplifier (LNA).

The T_{rec}^{DSB} of the same HEB was also measured at 6.5 K. We obtain a T_{rec}^{DSB} of 3530 K at the bias voltage of 2.5 mV, same as at 20 K, but at a slightly lower current (0.19 mA). Interestingly, the T_{rec}^{DSB} is only 12 % lower than the value at 20 K. The small difference between 6 K and 20 K should be attributed to the high T_c . The measured G_m^{DSB} is -6.7 dB at 6.5 K and is clearly higher than what was found (≤ -8.7 dB) from a NbN HEB at 5.3 THz at 4 K [28]. In contrast, the difference of T_{rec}^{DSB} between 5 K to 20 K was much larger and was 75 % for a HEB with a T_c of 31 K [14].

To understand the origin of the slow increase of T_{rec}^{DSB} from 6 K to 20 K, we measured both T_{rec}^{DSB} and G_{rec}^{DSB} of the HEB fixed at the biasing point of 2.5 mV and 0.19 mA by varying the temperature from 6.5 to 22.5 K. To keep the same biasing point, the LO power has to be reduced with increasing the temperature by about 2 μ W. Since we focus on the operating at 20 K, we discuss the data only up to this temperature. We find a very similar temperature dependence between T_{rec}^{DSB} and T_m^{DSB} (Figure 7.4), where there is an increase of 18 % for T_{rec}^{DSB} (between 6.5 K and 20 K), while 19 % for T_m^{DSB} . The ratio of the absolute value of the increase, 656 K for ΔT_{rec}^{DSB} and 249 K for ΔT_m^{DSB} , can be explained by the G_{opt} (-4.1 dB). However, both T_{rec}^{DSB} and T_m^{DSB} remain nearly constant below 10 K.

In essence, the temperature dependence of T_m^{DSB} originates from G_m^{DSB} and T_{out} , both of which decrease with increasing temperature, as shown in Figure 7.4. Furthermore, the G_m^{DSB} decreases faster than the T_{out} , leading to the increase of T_m^{DSB} with the temperature according to Eq. 2. Such temperature dependences are relatively unexplored experimentally although the dependence with the very limited number of data points was reported in [30]. In theory, one expects a decrease of T_{out} by increasing the operating temperature based on the hotspot model [31-33] because a bell-shaped electron temperature (T_e) profile along an HEB at a lower temperature becomes a flat one by increasing the temperature up to T_c , but simultaneously decreasing LO power for the fixed bias point. The flat T_e profile results in a lower effective T_e in the center of the HEB, which in turn decreases T_{out} since T_{out} is dominated by the thermal fluctuation noise ($\propto T_e^2$). With regard to G_m^{DSB} , one also expects it to decrease with increasing the

temperature because of the T_e profile and the reduced LO power. The behavior in our case is qualitatively in line with the simulation reported in [33].

Figure 7.4. Measured receiver noise temperature T_{rec}^{DSB} (at 1.7 GHz) in (a), derived mixer noise temperature T_m^{DSB} in (b), measured mixer conversion gain G_m^{DSB} in (c), and derived output noise T_{out} in (d) of the MgB₂ HEB mixer as a function of operating temperature.

The IF NBW of the HEB can be obtained from T_{rec}^{DSB} measurements in a wide IF range. Figure 7.5 (a) shows the P_{hot} and P_{cold} measured over an IF range of 0.2-14 GHz, from which the T_{rec}^{DSB} is derived and plotted as a function of IF in Figure 7.5 (b). The equation, $T_{rec}^{DSB}(f) = T_0(1 + (f/NBW)^2)$, is used to fit the T_{rec}^{DSB} data to obtain an NBW, which is $9.5 \text{ GHz} \pm 1 \text{ GHz}$. We believe the low signal-to-noise ratio at the IF can affect the absolute value. As a confirmation, we find the NBW of $11 \text{ GHz} \pm 1 \text{ GHz}$ of the same HEB at 1.6 THz LO and at 5 K, which agrees to the reported result [14]. The large fluctuations of P_{hot} and P_{cold} , highlighted around 8 GHz in an inset in (a), result in the larger peak/dip in (b), which is believed to be a technical issue in the IF chain, but not from the HEB.

Figure 7.5. (a) Measured receiver output powers of the MgB_2 HEB corresponding to hot and cold loads as a function of Intermediate frequency (IF) when it is in its optimal operating point and at 20 K. The inset zooms in the frequency range of 1-1.5 GHz and 8-8.5 GHz; (b) Receiver noise temperature as a function of IF. The orange line is the best fit of $T_{rec}^{DSB}(f) = T_0(1 + (f/\text{NBW})^2)$ to the data, where the NBW, noise bandwidth, is 9.5 GHz.

7.4 Discussion

The π -band $\Delta_\pi = 1.8$ meV and σ -band $\Delta_\sigma = 6.3$ meV of MgB_2 were reported for a T_c of 38.7 K [17], corresponding to the gap frequency of 0.87 THz and 3.05 THz, respectively. Assuming these two gap frequencies apply also to our HEB since our T_c is 38.4 K, one would expect a different pumped IV when it is at 5.3 THz, where the THz photons can break all the Cooper-pairs and can be uniformly absorbed, and when it is at 1.6 THz, the photons can only break the Cooper-pairs in the π -band and can thus be non-uniformly absorbed. Inset (b) in Figure 7.1 shows pumped IV curves at 1.6 THz and 5.3 THz measured at 5 K and 20 K, respectively, where the IV at 5.3 THz has a lower current than that at 1.6 THz at

the low bias voltages. This effect, as one would expect, is stronger at 5 K, while the two IV curves are exactly the same at the high voltages. The latter suggests that the pumped LO power is the same. The effect is analogous to the NbN HEB operated below and above its gap frequency, where the IV curves at two LO frequencies differ at low voltages [34]. In addition, the G_m^{DSB} at 1.6 THz is found to be slightly lower than that at 5.3 THz, which may further support that the double-gap effect plays a role in our experiment. The double-gap effect could be present in pumped IV of the MgB_2 HEB between 1.6 and 2.5 THz in [12] although the 2.5 THz is too close to the high gap frequency.

The measured T_{rec}^{DSB} will increase by less than 2% and thus remain nearly unchanged if the LNA is also operated at 20 K, where T_{IF} will increase from 4.7 K to 8.5 K. To compare the sensitivity of our HEB with the reported value (930 K) at 1.6 THz only [14], we also measured a T_{rec}^{DSB} of the same HEB at 1.6 THz and at 6.5 K, and obtained 2100 K, which is higher and is likely due to the narrower bridge width [35].

The sensitive MgB_2 HEB mixer with a large NBW, which can be operated at 20 K in a Stirling cooler [16], is promising for space applications. Based on the measured 3960 K, the expected, lowest T_{rec}^{DSB} of 2720 K at 5.3 THz by using the optimized coating lens ($\rightarrow$ 3470 K), the thinner beam splitter ($\rightarrow$ 2920 K), and also the antenna matched HEB resistance ($\rightarrow$ 2720 K), is 28 times lower than a Schottky diode mixer at 4.7 THz [36], but is only $\sim$ 2.5 times more than an NbN HEB mixer at 5.3 THz [20].

7.5 Conclusion

In summary, we have demonstrated a low noise MgB_2 HEB mixer operated at 5.3 THz LO and at 20 K. The measured receiver noise temperature, T_{rec}^{DSB} , is 3960 K, which can be further decreased to 2920 K for the same device by using an optimized coated lens and a 3 μm beam splitter. The T_{rec}^{DSB} has a weak temperature dependence because of the high T_c , and has only 12 % decrease in the optimal value when it reaches 6.5 K or below. The measured IF NBW is 9.5 GHz at 20 K. Additionally, the temperature dependences of the mixer conversion gain and output noise have been studied by varying the operating temperature from 6 to 23K. Finally, we observed different IV curves at low bias voltages, pumped at 1.6 and 5.3 THz, suggesting the presence of the two superconducting gaps in the thin MgB_2 .

See the supplementary material for the following: part A: the fabrication process of MgB_2 HEBs and part B: the description of the heterodyne measurement setup.

Supplementary material

1. HEB fabrication

The HEB devices are realized in two steps. First, the MgB_2 film was grown by the HPCVD at Chalmers University of Technology [18]. The film is 7 nm thick according to the growth rate. To minimize oxidation, the film, when taken out from the HPCVD chamber after the growth, is immediately loaded into a sputter machine, where an in-situ Au (20 nm) deposition is performed on the top of the MgB_2 film after a sputter cleaning.

Second, MgB_2 HEB devices were fabricated at Delft University of Technology. The fabrication starts with the definition of the contact-pads with e-beam lithography (EBL) and Au evaporation in combination with a lift-off process. Then, the spiral antennas are defined using a similar process, but by evaporating a thicker Au layer together with a layer of Ti on the top. The latter is to prevent etching of the Au antenna during the Ar Ion beam milling etching (IBME) to define the MgB_2 bridge width. Now, the Au layer of 20 nm (protecting the MgB_2) is removed using IBME, followed immediately by depositing a layer of Si_3N_4 (80 nm) in a sputter machine to avoid the oxidation of MgB_2 through the rest of the process. The etching mask to define the submicron-bridges is then patterned using EBL. Finally, the uncovered Si_3N_4 and MgB_2 are etched away using IBME to form MgB_2 bridges. Before the dicing of HEB chips, a thick layer of Si_3N_4 is sputtered to cover the surface of the chips except for the bonding pads to isolate MgB_2 bridges from water and air.

2. Measurement setup

The LO is the far-Infrared (FIR) gas laser at 5.25 THz. A voice coil attenuator together with a proportional–integral–derivative (PID) feedback loop is used to sweep the LO power to determine T_{rec}^{DSB} or stabilize the power to measure IF noise bandwidth (NBW). The LO entered a blackbody hot (293 K)/cold (77K) vacuum unit attached to the 4 K cryostat via a window and then was reflected by a 6 μm Mylar beam splitter. The vacuum setup is to avoid the high air absorption loss at 5.25 THz. The combined radiation (LO + hot/cold loads) propagates to the lens-antenna coupled HEB mixer through a QMC multimesh low pass filter with a cut-off frequency of 5.8 THz. It acts as a heat filter and is referred as the “multimesh filter” in Figure 7.2. The Si lens used has an anti-reflection (AR) coating, but designed for 1.6 THz. The mixer is mounted on a metal block, which is fixed on the 4 K plate of the cryostat, but with a relatively poor thermal interface. A heater together with a sensor is installed on the mixer block to elevate the local temperature of the mixer from 6.5 K to 23 K. The IF chain contains of a bias-T (0.2-18 GHz), a circulator (1.3-1.7 GHz), a cryogenic

low noise amplifier (LNA#1, 0.1-14 GHz), where the circulator is dedicated to G_m^{DSB} measurements. All of cryogenic IF components are well contacted to the 4 K plate thermally. The room temperature part of the IF chain includes two LNAs (LNA#2: 0.1-14 GHz and LNA#3: 0.1-12 GHz), a bandpass filter (BPF), a low pass filter (LPF), and a microwave power meter. The IF is filtered at 1.7 GHz by the BPF with a bandwidth of 85 MHz for T_{rec}^{DSB} and G_m^{DSB} measurements. Since the BPF is not capable of blocking the signals beyond 5 GHz, the LPF is added before the power meter. The IF chain has the total gain of 85 dB and the noise contribution of 4.7 K at 1.7 GHz.

The setup is also used for measuring IF NBW in the range of 0.2-14 GHz by removing the circulator, the BPF, the LNA#3, and the LPF, but replacing the power meter with a spectrum analyzer.

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Chapter 8

Concept study of a kilo-pixel heterodyne receiver for future space telescope

The observation time of an observatory is limited, especially for a space observatory. The lifetime of a space mission is limited by the budget constraints (for operations), fuel on board (for manoeuvring / pointing), and damage by radiation, such as cosmic rays, etc. For mapping purposes, an array of multi-pixel detectors will take less time to map a region of astronomic interest in the sky in comparison with a single detector. The time difference is proportional to the number of pixels if the sensitivity of the pixels is the same. In addition, multi-pixel detectors improve image fidelity because differences in pixel-to-pixel calibration are washed out. As multi-pixel detectors are common in the optical (e.g. the Hubble Space Telescope (HST) [1] and the Kepler space telescope [2]), near-IR (e.g. The Near Infrared Camera (NIRCam) for the James Webb Space Telescope (JWST) [3]), and the (sub)mm-wave continuum (e.g. the Submillimeter Common User Bolometer Array (SCUBA-2) for the James Clerk Maxwell Telescope (JCMT) [4]), it is desirable to develop a multi-pixel receiver for supra-THz region. For this reason, heterodyne array receivers have been developed for the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA) [5], and the balloon borne Galactic/Xgalactic Ultra long duration balloon Spectroscopic Stratospheric THz Observatory (GUSTO) [6]. However, the state of the art of heterodyne detector arrays is of the order of 10 pixels using superconducting NbN HEB mixers, operated in the supra-THz (1-6 THz). There are a number of technical issues restricting the size of arrays, such as the cooling capacity and local oscillator power available. Fundamentally, each pixel in an array receiver is a spectrometer, which contains a mixer, a local oscillator, an LNA, and a backend spectrometer at GHz frequencies, as discussed in the previous chapters. This is profoundly different from a direct detector, such as a transition edge sensor [7] and Kinetic inductance detector [8], which have already shown an array of $> 10^3$ pixels.

A concept of a large heterodyne array receiver of kilo-pixels has been proposed by the University of Arizona/SRON at a SOFIA workshop in 2020 [9]. Here we

perform a detailed concept study of the array for SOFIA and for the next generation of THz space observatories. This chapter is structured as follows. An overview of heterodyne array receivers in the THz is given in Section 8.1. The available technologies for building an array receiver, including array LO, focal plane HEB array, intermediate frequency (IF) chain, and backend components, are described in Section 8.2. A designed model for a kilo-pixel heterodyne array receiver is introduced in Section 8.3, together with the possibilities of using current technologies to achieve a kilo-pixel heterodyne array receiver.

8.1 Overview of heterodyne array receivers

There are two detection techniques for measuring THz radiation: cryogenic bolometers for continuum and heterodyne receivers for spectral lines. Arrays based on cryogenic bolometers have been operational since the mid-1990's, such as the Max-Planck-Millimeter-Bolometer (MAMBO-2) with 117 pixels at 0.25 THz on the IRAM 30 meter telescope [10], the SHARC-II with 384 pixels at 0.66/0.86 THz at the Caltech Submillimeter Observatory (CSO) [11], and the Submillimeter Common User Bolometer Array (SCUBA-2) instrument with 10,240 pixel at 0.35 THz and 0.66 THz at the James Clerk Maxwell Telescope (JCMT) [4]. Heterodyne array receivers based on superconducting Superconductor-Insulator-Superconductor (SIS) mixers and Hot Electron Bolometer (HEB) mixers are used at ground-based and space-based telescopes. An SIS mixer array, due to its high sensitivity, relatively large IF bandwidth, and availability of the local oscillator (LO), is widely used on ground-based telescopes. Review [12] lists the heterodyne arrays operating during the years 1988-2015. Ground-based telescopes equipped with SIS mixer arrays include CHAMP (4×4-pixel array at 0.48 THz) at the CSO [13], CHAMP+ (2×7-pixel array at 0.66/0.86 THz) for the Atacama Pathfinder EXperiment (APEX) [14], HERA (3×3-pixel array at 0.23 THz) at the IRAM 30 m telescope [15], SMART (2×4-pixel array at 0.49/0.81 THz) on the Kölner Observatorium für Submillimeter-Astronomie (KOSMA) 3 m telescope [16] and the NANTEN2 telescope [17], the HARP 4×4-pixel array at (0.32-0.37 THz) at the JCMT [18], and SuperCam (8×8-pixel array at 0.35 THz) at the Heinrich Hertz Telescope [19].

However, there is a limitation for the operating frequency of SIS mixers due to the energy gap of the superconducting materials. SIS mixers have worked with a high sensitivity up to 1.1 THz. Beyond this frequency, niobium nitride (NbN) HEB mixers are the mixers of choice because of their sensitivity and low LO power requirement, which operate at a wider frequency range (0.3-6 THz). An alternative for NBN mixers is a magnesium diboride (MgB₂) HEB mixer, as described in Chapters 6 and 7, which provide a wider bandwidth (11 GHz) than

NbN HEB mixers (3-4 GHz) benefit from its higher critical temperature 30-40 K, making it suitable for operating at frequencies above 4 THz.

Radiation above 1 THz suffers from water vapor absorption in the earth's atmosphere. Therefore, an observatory aiming for the frequencies beyond should be either from a high altitude airplane or balloon, or from space. The upGREAT array receivers at the SOFIA telescope are a 2×7 pixel array at the frequencies of 1.83–2.07 THz and a 1×7 -pixel array for 4.7 THz [5]. Another way is a balloon-borne telescope. The STO-2 telescope has a 2-pixel receiver at 1.4–1.9 THz and a single pixel at 4.7 THz respectively [20]. Its successor, the GUSTO telescope, to be launched in 2022, has three 2×4 pixel arrays at 1.4 THz, 1.9 THz, and 4.7 THz, respectively [6]. Both STO-2 and GUSTO are equipped with SRON and TU Delft's HEB technology.

There are also heterodyne array receivers either proposed or planned. HEterodyne Receiver for the Origins (HERO) instrument for the Origins Space Telescope (OST) plans to have two bands of 4×4 -pixel SIS mixer array at 0.47–1.26 THz range and four bands of 8×8 -pixel HEB mixer array at 1.24–4.75 THz range [21]. Large arrays operated at the frequencies below 1 THz are planned for ground based telescopes. CHAI for the Cerro Chajnantor Atacama Telescope (CCAT) plans to have a 64-pixel SIS mixer array at 0.46–0.82 THz range [22]. A 1000-pixel SIS mixer array at 0.66 THz aimed by the Kilopixel Array Pathfinder Project (KAPPA) has been proposed in [23], which has potential for the Atacama Large Aperture Submillimeter Telescope [24], Large Submillimeter Telescope [25], CCAT, and South Pole Telescope [26]. So far no one has studied or built a kilo-pixel HEB mixer array for a sub-orbital or a space telescope yet.

8.2 Summary of components for heterodyne arrays

8.2.1 LO source and multiplexers

There are two types of solid-state THz sources for LO applications. One is the THz source based on a frequency multiplier chain, and the other is a quantum cascade laser. A far-Infrared gas laser can be used as LO for the test purposes in the lab, but is not suitable for a real instrument in space because it is bulky and has a high dissipation power. We start with a frequency multiplier chain source, which usually starts from a source at a microwave frequency, e.g. 10 GHz, which is multiplied to about 100 GHz using a multiplier. At this frequency the signal is amplified by a power amplifier. Then it is further multiplied to a targeted THz frequency. In this stage, it often makes use of a multiplier chain, which combines a few doublers and triplers, in order to reach the THz frequency. The highest frequency which such a multiplier chain has reached is 2.7 THz [27]. The

advantages of multiplier chains are that they are capable of working at room temperature, that they are tunable with a fractional bandwidth of 15%-20%, and that they have a relatively low DC power dissipation [28]. However, with increasing frequency, the output power of frequency multipliers decreases rapidly due to the higher requirements on accurate design and fabrication at higher frequencies. The maximal output power of frequency multipliers reaches 1 mW at 1.6 THz [29], 60 μ W at 1.9 THz [30], and 18 μ W at 2.58 THz [31]. Although current progress is very impressive, this power is far too low for a kilo-pixel HEB mixer array, in particular, if the frequency becomes higher. Taking a typical NbN HEB mixer as an example, each pixel requires about 5-10 μ W directly from the source although the HEB itself needs only about 200 nW. The extra power is needed because of reflection or absorption by the optical components.

THz quantum cascade lasers (QCLs) are promising LO sources for HEB mixer arrays because of their high output power. THz QCLs have covered the frequency range from 1.2 THz to 5.0 THz although they are not tunable, and their output powers reach more than 200 mW (in continuous-wave mode as required for an LO) [32,33]. THz QCLs need to work at a cryogenic temperature (10-80 K) [34], but QCLs with a higher operating temperature have also been demonstrated, for instance, THz QCLs (at $\sim$ 4 THz) with a maximum operating temperature of 250 K in [35]. QCLs used for heterodyne instruments for SOFIA and GUSTO are operated at a temperature of $\geq$ 40 K, where there are compact, low dissipation Stirling coolers available. In general, the high output power of a THz QCL, e.g. > 10 mW, is not an issue. However, the challenge is to build a QCL, which not only has a high power, but also meets all other demands for an LO such as the beam pattern and the emitting frequency. The latter needs to be precise, not more than a few GHz away from a targeted spectral line due to the limited IF bandwidth of the receiver.

The beams of QCLs based on a metal-metal waveguide [36], e.g. used for GUSTO, are divergent ($\sim 20^\circ$) [37], and importantly deviate considerably from a fundamental Gaussian profile. A collimated, fundamental Gaussian beam is essential to match effectively to those of HEB mixers [38,39]. It also minimizes the stray light caused by reflections due to mismatch of the beams, and makes the optical design for an instrument more accurate. There are two methods to improve the divergence and the beam pattern, namely device patterning approaches and additional component approaches. Optimizing the laser structure achieves a narrower beam ($\sim 10^\circ$) and also a better beam pattern [40,41], so the power from the QCL can be used more effectively. The disadvantage of this approach is the complexity in the design and manufacturing of such QCLs. Adding optical components in front of a working QCL can also achieve a collimated, Gaussian beam, including using hollow waveguides or

hyper-hemispherical silicon lens mounted near the emitting facet of the QCLs [42-45], the combination of a spherical lens and a diaphragm [46], a back-to-back corrugated feedhorn filter [47], and a back-to-back lens filter. The latter was pioneered in Chapter 3. The disadvantage of the 2nd approach is that it needs additional alignment and a fraction of the power (50-70 %) from the QCL will be wasted.

Using a THz multiplier chain as LO for each mixer is possible and realistic if it is a small array (in the order of 20 pixels). For example, the two low frequency arrays on GUSTO are using an array of multiplier chain sources. But, it is difficult for a kilo-pixels because of the huge volume and cost.

Using a QCL as LO for each pixel is not an option because of two main reasons: a) all QCLs have to be operated at the exact same frequency, which requires a frequency-locking scheme for each QCL, thus is technically impossible; b) the total power dissipation will be too high to be accommodated by a modern cooler. Multiple beams from a single source can be achieved by quasi-optical dividers, including a succession of beam splitters and a phase grating (or Fourier grating) [48-51]. HARP on the JCMT uses a succession of beam splitters to achieve multiple beams [18]. The high frequency bands (4.7 THz) of SOFIA and GUSTO use a phase grating to divide one single QCL beam into multiple beams. A phase grating is capable of splitting a QCL beam into ~ 100 beams with 94% efficiency, which means 94 % of the power from the incoming beam is converted to the multiple beams, with fair power uniformity [52]. To generate kilo-pixel LO beams, using a single phase grating faces the problem of fabrication and power non-uniformity. Instead, one can use a combination of a few phase gratings and additional optical components to achieve kilo-pixel LO beams. For example, one can combine a 3×3 phase grating with a 11×11 phase grating in series. In this case, a single beam is first divided into 9 beams with a wide angular distribution by the 3×3 phase grating, and then the pointing directions of the 9 beams can be corrected by using reflection mirrors. After that, each of the 9 beams illuminates an 11×11 phase grating, which will eventually diffract 1089 beams in total.

8.2.2 Detectors

At supra-terahertz frequencies, the available mixers include Schottky diodes [53], hot electron bolometers (HEB) [54], terahertz quantum well photodetectors (QWP) [55], and QCL detectors. The latter can be used for dual-comb multi-heterodyne detection [56-58], which uses two QCLs consisting of a series of discrete, equally spaced frequency lines as the frequency combs to produce a multi-heterodyne spectroscopy. HEB mixers, due to their high

sensitivity, are the detector of choice for supra-THz astrophysics. They have been applied to the GREAT/upGREAT instrument on SOFIA, STO-2, and are being integrated in the GUSTO telescope. HEB mixers are also planned for the Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS) [59] and at HERO for OST. An HEB mixer uses the bolometric property of the superconducting-normal transition to achieve high conversion, low-noise mixing. It can operate at any frequency between 0.3-6 THz and does not have a practical operating upper frequency limit [12]. The NbN HEB mixers have demonstrated a relatively low double sideband noise temperature, from 300 K at 1.3 THz to 1150 K at 5.25 THz [60,61], which are below 10 times the quantum limit. Another advantage of HEB mixers is that they require a relatively low LO power (100-300 nW) [34]. The IF bandwidth of a NBN HEB mixer is typically 3-4 GHz, dominated by the thermal time constant of the HEB. The small IF bandwidth is a downside for the higher frequency applications, e.g., for 4.7 THz [OI] lines. Also, it requires a 4 K cooler because the critical temperature of NbN is about 8-10 K.

The drawbacks of a NbN HEB can be resolved by using an MgB_2 HEB mixer, which provides an IF bandwidth as large as 11 GHz, as demonstrated in Chapters 6 & 7. The critical temperature T_c of an MgB_2 HEB mixer is about 30-38 K. The higher T_c enables the mixer to work at a higher bath temperature, e.g. 20 K, where one can apply a compact, low dissipation power, space qualified Stirling cooler. On the one hand, the HEBs with the higher T_c have a higher LO power requirement, which is 10 μW for the HEB, and also have higher intrinsic noise, leading to a factor 2-3 times higher receiver noise temperature than what was reported for NbN HEBs. Both issues are R&D topics and are in progress. For the kilo-pixel HEB mixer array, we focus on using NbN HEB mixers, which have a high TRL and are more mature.

There are two methods to couple an RF signal and an LO signal into a HEB mixer: waveguide coupling and quasi-optical coupling. For the method of waveguide coupling, a feedhorn antenna is used to couple radiation from free space into a waveguide mounted with an HEB [62,63]. The advantage of waveguide coupling is that it provides single mode structure and a high Gaussicity of the beam, which enables outstanding coupling to the telescope [64]. However, with increasing frequency, not only the scale of the waveguide is reduced, which makes the process of fabrication difficult, but also the HEB device substrates need to be extremely thin (a few micrometers) to avoid THz waves propagating in the substrate channel [65]. For the method of quasi-optical coupling, a lithographic planar antenna is integrated with an HEB on a chip. Commonly used lithographic antennas include broadband double-slots and spiral antennas [66] due to their good performance and easy manufacturing. The incoming radiation is coupled into the chip that is mounted on a substrate and is always placed in the focal

plane of a collimating reflector or lens. However, when the incident angle is larger than the critical angle, the radiation will be reflected at the substrate-air interface and trapped in the substrate, causing poor radiation patterns and low coupling efficiencies. To solve this problem, the chip is attached to the back side of an elliptical lens or a hyper-hemispherical lens, which is the same material or has the same dielectric constant as the substrate. In comparison with waveguide coupling, quasi-optical coupling is more suitable for detectors operating at higher frequencies due to their easy fabrication and lower cost. As to be explained in the next section, they are also more suitable for a large array.

8.2.3 Elliptical lens arrays

With the advantages of easy fabrication and lower cost, the lens-antenna coupling scheme is more desirable for a large mixer array. Applying a single, large diameter lens to couple the radiation to an array is not ideal because the illumination is non-uniform among the mixers. Furthermore, the size of the mixer array will be limited by the optical aberration of the lens [67]. Therefore, a desirable and effective way is to make use of a lens array, which is aligned to the mixer array. Then the fabrication of a kilo-pixel lens array is an issue worthy to discuss.

There are different techniques to fabricate a lens array, including photolithography and deep reactive etching processes [68], direct machining [67,69], laser micro-machining [70,71], 3D printing [72,73], the meta-material flat lens [74], and the GRIN (Gradient Refractive INdex) lens array [75,76] etc. Photolithography is capable of fabricating hemispherical lenses with a limited height of a few hundred microns. Making use of a leaky-wave waveguide feed, Llombart et al. demonstrated an extended hemispherical lens antenna, which requires only a small part (30°) of the lens surface, reducing the height of the lens to a few hundred microns, making fabrication using photolithography possible. This lens antenna has been fabricated and characterized at 1.9 THz [77].

Nitta et al. have demonstrated a 102-pixel 2.04-mm-diameter extended hemispherical silicon lens array at 440 GHz [67] and a 721-pixel 1.64-mm-diameter extended hemispherical silicon lens array at 220 GHz using direct machining technology [69] for a microwave kinetic inductance detector (MKIDs) array. The lens profile errors increase (from 10 μm to 30 μm) with the number of pixels because the end mill used in the machine was worn out due to the long progression (from 45 hours to 90 hours)

Laser micro-machining technology can also be used to fabricate a silicon lens array. Yates et al. demonstrated an 880-pixel array of lens-antenna coupled

MKIDs at 350GHz [70] and a 961-pixel array at 850 GHz [71] for operation in the AMKID camera for the APEX telescope [78]. The silicon lens arrays in both detector arrays are fabricated using laser ablation [79]. The fabrication accuracy of the lens surface is $\sim 10 \mu\text{m}$ for a 3488-pixel large array (private communication S. Yates/in preparation).

3D printing technology is capable of printing an arbitrary shape. The most common materials for 3D printing are photosensitive resin, nylon, ABS plastic, etc. A 340 GHz 2x2 pixel 3D printed extended hemispherical lens (with 2.65 mm diameter) array has been made with a low dielectric constant ($\epsilon = 3.5$) polymer material in [73]. This material may not be suitable for supra-THz application due to the losses caused by polymer materials.

Besides lens arrays, meta-material based flat lens arrays have been explored, where the wavefront of light is shaped by designing planar and ultrathin metamaterials to manipulate the propagation of reflected and refracted light by the phase discontinuities created in a monolayer of metamaterial [74,80]. A 5×5 metasurface-based lens array, patterned on a silicon substrate, was fabricated and tested at frequencies from 0.35 to 1.05 THz by Wang et al [74]. However, this type of meta-surface lens array needs accurate alignment on the focal plane and the mixer array substrate, which makes the alignment for a lens-antenna coupled mixer array complicated. A more desirable way is to attach the wafer of the mixer array on the back side of the lens array. A Silicon Etched GRIN Lens allows a detector attached to the back side of it and more than 90% of the radiation to be transmitted from antenna to the lens. The gradient refractive index is achieved by etching holes with different diameters on a sub-wavelength pitch in a dielectric material such as Si by use of the deep reactive ion etching process [75,81,82]. Pisano et al. simulated and fabricated a 19-pixel hexagonal lens array for the 90 and 150 GHz bands and the simulation shows losses ($\sim 20\%$) into the Si. This approach is promising for long-wavelength ($\lambda \gtrsim 2 \text{ mm}$) applications, but for the short wavelength of our interest, the size of the holes in the silicon becomes smaller and thus the fabrication becomes problematic. The same group then developed Silicon-Embedded Metal-Mesh GRIN Lenses formed from metal squares patterned on stacked Si substrates by use of photolithography, thus enabling application to higher frequencies. This lens array concept is adopted from metal-mesh phase-delay technology and the metal squares are formed to create phase-delay.

Among the techniques described so far, photolithography, direct machining, laser ablation, and metal-mesh phase-delay technology can be used to fabricate silicon lens arrays. Photolithography has the limitation of fabricating silicon lenses with a height of the order of hundreds of microns, thus achieving a relatively small surface error for the fabricated lenses. To use this technology,

an air cavity between the double slot and the silicon lens is needed to generate a leaky wave for creating a directive beam pattern. However, for the IF bandwidth of an HEB, it needs a thermal cooling process to a substrate, namely silicon. Otherwise the HEB will have too small an IF bandwidth. The metal-mesh lenses are also fabricated using photolithography, thus enabling application at higher frequencies. However, until now no silicon-embedded metal-mesh lens has been demonstrated at frequencies $>1\text{THz}$. Direct machining has been used to fabricate a 721-pixel lens array as mentioned before, but the mean surface error is approximately $30\text{ }\mu\text{m}$, which could be reduced by changing the end mill more frequently during the fabrication process or changing to end mills with a higher hardness, such as diamond. Both ways will increase the cost of the fabrication. With a high resolution, laser ablation technique achieves a smaller surface error than direct machining. For a 3488-pixel lens array to couple the radiation to MKIDS demonstrated at SRON, the surface error is $\sim 10\text{ }\mu\text{m}$. Therefore, a lens array fabricated by laser ablation is a good choice for building a kilo-pixel lens-antenna coupled HEB array at the moment. However, a meta-material based flat lens array should be exciting and may be ready in the near future.

8.2.4 Low noise amplifiers

The IF output power of a mixer is very low, less than -130 dBm [83], thus a series of low noise amplifiers (LNAs) are equipped in the IF chain to amplify the power level to be sufficiently high for the spectrometer. To reduce the noise contribution from the LNAs, the first LNA is working at cryogenic temperature, which is either the 4 K or 20 K cooling stage. For typical closed-cycle coolers, the cooling power is 1.5 W at 4 K ambient temperature [84] and 12 W at the 20 K stage [85]. Therefore, to distribute the cooling power to 1000 pixels, defining the power consumption of each LNA to be less than 1.5 mW at 4 K and less than 12 mW at 20 K is necessary. The available cryogenic LNAs are InP HEMTs (High Electron Mobility Transistors), GaAs HEMTs, and SiGe HBTs (Heterojunction Bipolar Transistors) [86-88]. Hybrid HEMT based LNAs have shown a low power consumption of 0.3 mW at 5 K with a bandwidth of 4-8 GHz and a low noise temperature of 3 K [86]. Hybrid SiGe HBT based LNAs also have shown a low power consumption of 0.3 mW at an ambient temperature of 15 K with a bandwidth of 1.8-3.6 GHz and with a noise temperature of 5 K [89]. To reduce the total volume of the cryogenic LNAs (one LNA has a size of $10\times 20\text{ mm}^2$ to $0.5\times 1\text{ mm}^2$) and to reduce the cost in mass production, monolithic microwave integrated circuit (MMIC) LNAs (one MMIC LNA has a size of $0.5\times 1\text{ mm}^2$) are favorable. Table 1 lists MMIC LNAs based on HEMTs and SiGe HBTs developed in the last decade. The SiGe HBT based MMIC LNA in [92] has shown a lower power consumption of 0.76 mW and a low noise temperature of 8 K at 18 K with

a bandwidth of 4-8 GHz. It is promising to estimate the performance of such MMIC LNAs at 4 K ambient temperature and within a bandwidth of 0.5-4 GHz. Another SiGe HBT based MMIC LNA has shown a reasonable power consumption of 8.3 mW at 19 K with a suitable bandwidth of 0.5-5 GHz for NbN HEBs and with a noise temperature of < 8 K [90], and this MMIC LNA seems to be the best candidate if one operates LNAs at the 20 K stage.

Table 8.1. MMIC LNAs based on HEMTs and SiGe HBTs technologies developed in the past decade.

Technology reference	Frequency Band (GHz)	Gain (dB)	Noise temperature (K)	Power consumption (mW)	Ambient temperature (K)
SiGe HBT, [90]	0.5– 5	25	< 8	8.3	19
InP HEMT, [91]	0.5 – 13	38 – 44	< 7	15	15
GaAs HEMT, [87]	2 – 14	25	< 10	3	20
SiGe HBT, [92]	4 – 8	30 26	8	0.76 0.58	18
SiGe HBT, [93]	2 – 4	28	3.3 – 4	3	16.5
InP HEMT, [94]	0.3 – 14	42	3.5	12	4

8.2.5 Backend spectrometers

Digital Autocorrelation Spectrometers, Chirp Transform Spectrometers (CTS), and Acousto-optical spectrometers (AOS) have been used in astronomical instrumentation [9,13,95]. However, they are either bulky or consume too much DC power. Field-programmable gate array (FPGA) based Fast Fourier Transform (FFT) spectrometers have shown good performance at the APEX telescope [96] and the GREAT instrument on SOFIA [97] with a power consumption of less than 20 W. FPGA-based FFT spectrometers use fast analog to digital converters (ADCs) to sample the IF signal, and currently the speed of the ADC samplers allows 4 GHz IF bandwidth with 128k channels and are approaching 5 GHz [12]. Complementary metal–oxide–semiconductor (CMOS) chip-based spectrometers have demonstrated a low power consumption of 1.5 W and their IF bandwidth can reach up to 3 GHz with 4196 channels [98]. This technology, only demonstrated very recently, is a promising spectrometer option for a large heterodyne array, because of the low power consumption, small volume, and its light weight.

8.3 Concept of kilo-pixel lens-antenna coupled HEB heterodyne receiver

This section describes a design concept for a kilo-pixel heterodyne array receiver. We choose one particular THz frequency to start with. The [CII] line at 1.9 THz is the richest emission line associated with the life cycle of the interstellar medium in galaxies, and NbN HEB is the most sensitive detector at this frequency with a low LO requirement, thus we focus on developing a heterodyne receiver concept for a kilo-pixel NbN HEB array at 1.9 THz, which includes an LO array and a 3D demonstration model of a focal plane array, but uses 8×8 pixels as for illustration. The focal plane array contains a lens array, mixer array, and MMIC LNAs. The choice of the techniques to achieve each part will be addressed. The current 14-pixel heterodyne array receiver in SOFIA is capable of mapping a one-square-degree region in the [CII] line of the Orion molecular cloud, which reveals that the wind from a newborn star prevents nearby stars from forming [99]. With an increase of the pixel number, larger regions of the sky can be observed within the same time.

8.3.1 LO source and distribution

As mentioned in Section 8.2.1, a QCL is the most promising LO source due to its high output power. As LO, we choose a QCL. A high power QCL at 1.8 THz, which is in principle applicable for 1.9 THz, has been reported [100]. Such a QCL can emit a power of 28 mW to 2mW when the operating temperature increases from 10 K to 165 K. We require a 1.9 THz QCL with an output power of 10 mW around 45 K, as to be explained. This temperature can be easily facilitated by either a Stirling cooler or the 40 K stage of a pulse-tube cooler.

To effectively couple the LO source to the HEB array, a beam divider is needed. Using the combination of several phase gratings or using a series of beam splitters to achieve a kilo-beam LO seems to be very challenging. One idea to pump a kilo-pixel mixer array, e.g., a 32×32 -pixel array, is to produce a big uniform square beam in intensity. A square flat-top beam was reported by using a phase grating encoded on a spatial-light modulator and a $4f$ system in [101,102]. We propose to take advantage of a Fourier grating to generate multiple diffracted beams, and the exact number of diffracted beams is not important as long as they overlap with each other and form a square flat-top beam when reaching the HEB array. When the distance between the two adjacent beams becomes equal to the beam waist of each diffracted beam, the output beams overlap and form a flat-top square beam at the focal plane, as illustrated in Figure 8.1, where we use the Fourier grating producing 9×9 diffracted beams demonstrated in Chapter 4 as an example. To create the

collimated, flat-top profile beam, two conditions need to be satisfied: 1) the grating should be placed on the beam waist position of the incoming beam to ensure that the phase center of the multiple deflected beams and their beam waist are both located in the grating plane, which is the focal plane of lens 2 in Figure 8.1 (a); 2) the divergence of the overall profile of the multiple deflected beams should be designed to be the same as the divergence of each individual beam based on the grating equation: $D(\sin\theta_m - \sin\theta_i) = m\lambda$, where D is the periodicity of the grating, θ_m is the angle of the m 'th diffraction order, θ_i is the incident angle with respect to the normal of the grating, and λ is the wavelength.

Figure 8.1. (a) Schematic of using a Fourier grating to create a square, flat-top beam. We take a 9×9 -pixel Fourier grating as an example. The mixer array has 32×32 pixels, but here we only draw 8 pixels in one of the directions for simplicity. (b) The bottom 9 curves are the 1D profiles of the diffracted beams by the Fourier grating. The profile on the top is the resulting beam by overlapping all the diffracted beams.

One thing we care about is how much of the power from the QCL is effectively coupled to the HEB mixers, namely, the efficiency of the LO power to detector array. The two collimating lenses could use Si lenses with anti-reflection (AR) coatings due to their high transmissivity $\sim 91\%$ [103,104]. and the Fourier grating has an efficiency of $\sim 94\%$. So the transmission of two lenses and a grating is $0.91^2 \times 0.94 = 78\%$. As shown in Figure 8.1 (b), only the flat part of the beam is used to pump the array mixer, which contains 65% power of the entire beam. Therefore, the efficiency of the LO distribution system is expected to be 51%. Besides, a beam splitter is necessary to reflect the LO signal, which will combine with the sky RF signal to the detector array. We expect 5% of the LO power to reach the detector by taking all the losses due to the $6 \mu\text{m}$ beam splitter (8%), window (86%), heat filter (86%), and the antenna-HEB (90%). With an AR coating, the optical loss of the lens array can be omitted. The coupling

efficiency between a flat-top beam and the mixer array can be calculated by this equation:

$$\eta = \frac{\sum_{i,j} (E_1(i,j) \cdot E_2(i,j))^2}{\sum_{i,j} (E_1(i,j))^2 \cdot \sum_{i,j} (E_2(i,j))^2} \quad (8.1)$$

Where $E_1(i,j)$ and $E_2(i,j)$ are the electric field of the flat-top beam and the far field beam pattern of the lens-antenna, respectively. The latter is a nearly fundamental Gaussian beam [38,39]. Based on this equation, the coupling efficiency can reach >80%. So the total efficiency of the power of the QCL to the mixer array of 1000 pixels is 2%. Assuming each NbN HEB requires 200 nW, similar to what is required for GUSTO, we then conclude that the required power from the QCL is 10 mW, which is feasible by using a QCL, such as the one in [100].

8.3.2 Focal plane array at 4 K

The kilo-pixel mixer array requires a creative approach since adding individual HEB mixers in an array mixer block, taking the same approach as for GUSTO, will not be realistic. It is technically not possible to align all the mixers in the same pointing. We propose a wafer approach where all HEBs are fabricated on a wafer, being similar to a direct detector array (e.g., kinetic inductance detectors [8]). Assuming a pitch size of each pixel of 3 mm, a 32×32 HEB array will require a wafer of > 100×100 mm², which is commercially available [105]. In view of the success of the combination of a Si lens and Si HEB chip with an antenna, we choose a Si wafer for the HEB array. This array can also be divided into 4 sub-arrays of 50×50 mm² as an alternative. The lens array will also be defined on a Si wafer. To better illustrate this, Figure 8.2 (a) and (b) show an example 3D demonstration model of an 8×8 pixel focal plane array, including three layers, the lens array, the mixer array, and the MMIC LNA array. The distance between the neighboring HEBs equals the distance between the two lenses, and the four marks on the mixer array are used to align the two wafers. Coplanar waveguides (CPWs) defined by lithography extend from an HEB to the bonding pads, located outside of the HEB array area in the wafer. To read out the IF signal, a PCB circuit board containing a MMIC LNA array is attached to the mixer array chip. The PCB board has openings or holes in the places where HEBs are located, allowing the HEBs and the bonding pads to be exposed and to add the bonding wire from the pads to the CPWs in the PCB board. The CPWs in the PCB board guide the IF signal to the MMIC LNAs, in which the signal is amplified and transmitted to the SMP connector and then to the room temperature electronics. The 3D demonstration model of a single pixel is depicted in Figure 8.2 (c) and (d), and the size is exaggerated for clarity.

Figure 8.2. (a) (b) Two different views of a 3D demonstration model for a 8×8 pixel focal plane array. (c) (d) Two different views of a 3D demonstration model for a single pixel. (e) Top view of a 8×8 pixel lens array. (f) Bottom view of a 8×8 mixer array. (g) Bottom view of a 8×8 MMIC LNA array. The DC bias is connected by bonding wires to the bonding pads on the MMIC LNAs.

Figure 8.2 (e) shows an 8×8 pixel lens array as an illustration because a kilo-pixel is hard to illustrate. The diameter of a single lens in the array is 3 mm and all the lenses are arranged closely to each other since the pitch size also determines the spacing of the array beams towards the sky [12,34]. The total size for a lens array containing 8×8 pixels is 27×22 mm² (refer to Figure 8.2(e)), which becomes 99×81 mm² for a 32×32 pixel lens array. A 32×32-pixel lens array can be fabricated using laser ablation. Figure 8.2 (f) shows the 8×8-pixel HEB array, the bonding pads, and the CPW connecting the HEB and the bonding pads. The mixer array is based on double-slot coupled NbN HEBs due to its linear polarization and excellent symmetric beam pattern [106]. The dimension of a double-slot antenna for 1.9 THz is around 0.04×0.14 mm², therefore there is ~2.5 mm spacing between two adjacent HEBs. There are several CPWs passing in parallel through the 2.5 mm area. When they are too close to each other, there will be crosstalk via mutual inductance between neighboring CPWs [107], which refers to the signal current in one CPW coupling to the neighbors. In this example of 8×8-pixel mixer array, there are maximally 4 CPWs in the 2.5 mm space, indicating 625 μm space for each CPW. For a 32×32-pixel mixer array, the maximum number of parallel CPWs becomes 16, and the space for each CPW becomes 156 μm. Since the effective width of one CPW line, including the central conductor, two gaps, and two ground planes, is usually less than 50 μm, a 156 μm separation between two CPWs is large enough to eliminate the mutual inductance [108].

Figure 8.2 (g) shows the PCB board with 64 MMIC LNAs connected with SMP connectors. The MMIC LNAs are based on an SiGe HBT due to its low power consumption (< 0.8 mW) [92] although their operation frequency should be designed for 0.1-3 GHz. The connection from the mixer array chip to this PCB board is through bonding wires from the bonding pads in the mixer array to the CPWs in the PCB board. The spacing in the PCB board is even larger than the mixer array chip, therefore the crosstalk between CPWs is not an issue. The typical size of a SiGe HBT MMIC LNA is 0.5×1 mm², and the diameter of a SMP connector is ~ 4 mm. A PCB board can be large enough to contain a 1024-pixel MMIC LNA array.

8.3.3 Room temperature IF chain and backends

A flexible RF cable with a thin metal-film developed for GUSTO [9] could be used to connect the 4 K part, through 20 K, then to the IF chain at room temperature. The room temperature LNA is not critical and can benefit from the development of the fifth generation (5G) of telecommunications networks, where the power consumption of the LNA is pushed down to an order of mW for each [109]. Due to the small size (~ 120 cm³), low weight (~ 120 g), and low power consumption (1.5 W) of the CMOS chip-based spectrometer [110], it is feasible to design the kilo-pixel array. However, the total power of 1500 W for the 1000 spectrometers is still challenging for a satellite, but possible for SOFIA. The bandwidth of the state of art CMOS chip-based spectrometer is 3 GHz with 4196 channels, which corresponds to 474 km/s source velocity at 1.9 THz which is sufficient for science questions related to the disk of our Galaxy, and the disks of nearby galaxies [110].

8.4 Summary

This chapter summarizes the available technologies to build a kilo-pixel heterodyne array receiver. A concept of such an array receiver is proposed. The focal plane array consists of three layers: the lens array on a Si wafer, the HEB array on a Si wafer, and the MMIC LNA on a PCB layer, which are aligned and closely stacked. The mixers are twin slot antenna coupled NbN HEBs operated at 4-5 K. The LO will be illuminated by the uniformly distributed square beam, which will be realized by a 1.9 THz QCL of 10 mW and a Fourier grating. A closed-cycle pulse-tube cooler with a cooling power of 1.5 W at 4 K temperature is required and the cryogenic MMIC LNAs are designed to be at 4 K. An alternative is to arrange all the cryogenic MMIC LNAs at the 20 K stage of the cooler. The newly demonstrated CMOS chip-based spectrometers are chosen to be the backend spectrometers of the array. The total dissipation power of 1500 W for

the 1000 spectrometers at room temperature is very demanding for a space observatory, but should be possible for an airborne observatory, such as SOFIA. Furthermore, the meta-material flat lens array is very attractive. If this technology is ready, the focal plane array will be more easily integrated with the detector array which will reduce the cost considerably. MgB_2 mixers can raise the operating temperature to about 20 K, so that a compact, low dissipation Stirling cooler(s) can replace the closed-cycle pulse-tube cooler.

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Chapter 9

Conclusions

Terahertz spectroscopic observations (0.3-10 THz) with a high spectral resolution ($R \sim 10^6$, corresponding to a velocity resolution $\Delta v \sim 300$ m/s) can provide a wealth of information, helping us to answer key astrophysics questions, such as the condition and rate of star and planet formation and the evolution of galaxies. Fine structure lines at supra-THz region (1-6 THz), such as the [CII], [NII], and [OI] lines, are unique features, therefore, supra-THz observations provide us with distinctive information, which cannot be obtained by lower-frequency existing observatories, e.g., Atacama Large Millimeter/submillimeter Array (ALMA) [1]. Due to the high sensitivity at supra-THz region and the capability of achieving a very high spectral resolution of $R \sim 10^6$, single pixel and array heterodyne receivers (on the order of 10 pixels) based on a superconducting hot electron bolometer (HEB) are commonly used at telescopes to detect terahertz spectral lines from the sky. The atmospheric absorption of the supra-THz radiation makes it necessary to operate heterodyne array receivers at a high altitude airborne or balloon borne observatory, and ultimately at a space-borne observatory. The lifetime of space observatories is limited by the budget constraints (for operations), fuel on board (for manoeuvring / pointing), and damage by radiation, such as cosmic rays, etc. For example, the life time of the Herschel Space Observatory was limited to 4 years by the availability of liquid Helium [2] that cooled the detectors to below 4 K. Therefore, for any observatory, it is important to use observatory time effectively. A single pixel detector takes much more time to map a region in the sky than an array. The difference is simply proportional to the number of pixels in the array. My thesis addresses some key technologies needed to enlarge the size of an heterodyne array. But it also explores a novel HEB mixer, allowing it to be operated at a higher temperature than before. The latter can make use of a different cryogenic technology, increasing the lifetime of the space observatory and reducing the cost. In essence, my Ph.D. thesis has succeeded in addressing or making significant progress on four important questions in modern THz heterodyne technology.

The first contribution is to shape the non-ideal beam of a THz quantum cascade laser (QCL) as a local oscillator (LO) to a Gaussian beam. The LO, which provides a reference signal for heterodyne mixing, is an essential component in a heterodyne array receiver. QCLs are the only THz sources with high output power suitable for a large array up to 1000 pixels. They can be operated at ≥ 40 K and are able to deliver an output power of more than 200 mW. However, until now the output beam has still not been ideal. The QCL community is optimizing the laser structure in order to produce a high-quality output beam, i.e., a collimated Gaussian beam. Meanwhile, the method of adding an external optical component to the QCLs to achieve a high-quality beam is also under study. Chapter 3 in this thesis pioneered a terahertz spatial filter, consisting of two elliptical silicon lenses mounted back-to-back (B2B) and an opening aperture defined on a thin gold layer between the lenses, to shape the beam from a QCL to a fundamental Gaussian beam. The performance of the B2B lens system is investigated using an unidirectional antenna coupled 3rd-order distributed feedback (DFB) QCL developed in Prof. Qing Hu's group at MIT [3], and the B2B lens system is able to filter a non-ideal beam to a nearly fundamental Gaussian beam with an efficiency of more than 30%. The Gaussian beam increases the coupling efficiency to HEBs, and makes the design of the subsequent optical system more accurate. In particular, it is also crucial to form multiple beams using a phase grating since a Gaussian input beam to the grating avoids overlap between the individual diffracted beams. The future NASA mission Galactic/Xgalactic Ultra long duration balloon Spectroscopic Stratospheric THz Observatory (GUSTO) [4] could use such a beam filter. Such a beam filter is very helpful for future heterodyne instruments at high frequencies.

The second contribution is to demonstrate a phase (or Fourier) grating to generate 81 beams in the supra-THz region for LO applications, which has never been reported in the literature before. A heterodyne array receiver needs an array of LO beams. Using a separate QCL for each mixer in an array with more than a few pixels is not realistic. Therefore, we developed a phase grating to divide one QCL beam into multiple beams in Chapter 4. A Fourier grating producing 9×9 diffracted beams is demonstrated, which achieves a good uniformity among the diffracted beams and a high diffraction efficiency of 94 %. Such a combination of a Fourier grating and a QCL can create an LO array with about 100 pixels. In addition, Chapter 5 addresses the bandwidth issue of a phase grating. We took the grating at 4.7 THz designed for GUSTO to address this problem. By simulations using COMSOL Multiphysics, we found the bandwidth of this Fourier grating to be 250 GHz, which corresponds to 15,000

km/s linear velocity, sufficient for many astronomical applications. The outcome of this work has provided useful information for the design of the HETerodyne Receiver for the Origins (HERO) instrument for the proposed Origins Space Telescope (OST) [5]. Furthermore, the method we have developed could be used to calculate the bandwidth of Fourier gratings at other THz frequencies.

The third contribution is to demonstrate a low noise and large IF bandwidth MgB_2 HEB mixer at 5.3 THz, which can be operated at a higher temperature than a NbN HEB. The NbN HEB mixers used so far have a typical IF bandwidth of 3-4 GHz, which is not sufficient for detecting lines at a higher THz frequency, e.g., 4.7 THz. Besides, with $T_c=8\text{-}10$ K, the NbN HEBs have to be operated in a 4 K cooler. Chapters 6 & 7 demonstrated HEBs based on superconducting MgB_2 films with a high sensitivity, a large IF bandwidth, and the capability of operating at 20 K or above. Using HEBs fabricated at Technische Universiteit Delft based on MgB_2 films with a T_c of 33.9-38.4 K, developed by Prof. Serguei Cherednichenko's team at Chalmers University of Technology, we measured receiver noise temperatures of 2590 K at 1.63 THz and 3290 K at 2.52 THz at 5 K bath temperature. The latter is the first measured receiver noise temperature data at 2.5 THz reported for MgB_2 HEBs so far. The receiver noise temperature increases with increasing frequency due to a higher optical loss. Our results are higher than the best MgB_2 HEB (930 K at 1.63 THz) demonstrated at Chalmers University of Technology [6], but lower than the results (3600 K at 1.9 THz) obtained by Dr. Daniel Cunnane's group at NASA Jet Propulsion Laboratory [7]. We succeed in measuring the intermediate frequency (IF) noise response over a wide range of 0.2 to 14 GHz. We measured an 11 GHz IF noise bandwidth, which is considerably larger than achieved for an NbN HEB and which also agrees with what Prof. Serguei Cherednichenko's team has reported. However a real breakthrough is the work at 5.3 THz in Chapter 7, which shows the first measured noise temperature of 3960 K at 5.25 THz. The latter can be easily reduced to 2720 K by replacing two optical components in the receiver and by re-defining the antenna matched HEB resistance. It is interesting to stress that the result was obtained at 20 K although such an HEB can work through a wide temperature range from 4 to 35 K. Operating an HEB at 20 K is particularly interesting and encouraging because of the availability of a compact, low mass, low dissipation, space qualified Stirling cooler. Using the Stirling cooler instead of a liquid helium cryostat, e.g. the one used in Herschel, to cool the HEBs will be revolutionary and will open new space opportunities, such as the next generation of THz observatories with a number of telescopes operated as an interferometer in space [8]. The receiver noise temperature of 2720 K at 5.3 THz

is 28 times lower than a Schottky diode mixer at 4.7 THz, but is only ~ 2.5 times more than a NbN HEB mixer at 5.3 THz.

The fourth contribution is the detailed concept and design study of a kilo-pixel HEB array receiver for the Stratospheric Observatory for Infrared Astronomy (SOFIA) and potentially for a future THz space observatory. Although state of the art heterodyne array receivers, e.g., upGREAT in SOFIA [9] and GUSTO, reached an array of the order of 10 pixels, the community is pursuing to build larger heterodyne array receivers. A concept of a kilo-pixel heterodyne array receiver has been proposed by the University of Arizona and SRON Netherlands Institute for Space Research at a SOFIA workshop in 2020. In Chapter 8, we designed and analyzed a kilo-pixel heterodyne array receiver, which has a focal plane array integrating a micro-lens array on a Silicon wafer to an array of HEBs on another Silicon wafer, and a QCL-phase grating LO to form a square, flat-top beam for the entire array. The IF chains include an array of the cryogenic monolithic microwave integrated circuit (MMIC) low noise amplifiers operated at 4 K and the newly demonstrated complementary metal-oxide-semiconductor (CMOS) chip-based spectrometers at room temperature. The total dissipation power of 1500 W for the 1000 spectrometers at room temperature is very demanding for a space observatory, but should be possible for an airborne observatory, such as SOFIA.

Based on the work in this thesis, we move a step further to build large heterodyne array receivers (100-1000 pixels) and provide a promising HEB mixer for an airborne or space-borne THz interferometer. To utilize our work in real space applications, the following aspects could be further investigated:

- 1) The scheme of using several Fourier gratings to generate kilo-pixel beams or using one Fourier grating to generate a square flat-top beam could be designed and characterized, and the coupling efficiency between the generated beams and the lens-antenna coupled HEB should be studied.
- 2) To use the MgB_2 HEB mixers in an array receiver, the reproducibility and the uniformity of their performance should be studied by fabricating and measuring more devices. Besides, the stability of MgB_2 HEB mixers should be analyzed by Allan variance.
- 3) The combination of QCLs, Fourier gratings, array MgB_2 HEB mixers, and the 20 K Stirling coolers could be investigated for utilization in a future airborne or space-borne THz interferometer.

- 4) The performance of a lens-antenna coupled HEB using a meta-material flat lens could be studied, which makes the integration between the lens array and the detector array easier and also reduces the cost considerably for a large heterodyne array receiver.

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Nederlandse Samenvatting

Verschillende diersoorten op aarde zien een ander beeld wanneer ze naar de sterrenhemel kijken, omdat hun ogen gevoelig zijn voor andere frequentiebanden van het elektromagnetische spectrum. Andere elektromagnetische frequentiebanden bevatten andere informatie. Op dezelfde manier, als wij een astronomische telescoop gebruiken om het heelal te observeren, hopen we elektromagnetische golven te zien in verschillende frequentiebanden zodat we ons universum beter leren begrijpen. Bijvoorbeeld, de Hubble Space Telescope (HST), nu in gebruik, detecteert licht van de zichtbare frequentieband, de James Webb Telescoop (JWST) gaat de infrarode golfband detecteren, en de Atacama Large Millimeter/submillimeter Array (ALMA) in Chili, detecteert de millimeter- en submillimeter golfband. De Five-hundred-meter Aperture Spherical radio Telescope (FAST) (in Guizhou, China), en de Westerbork Synthesis Radio Telescope (WSRT) en Low Frequency Array (LOFAR) in Nederland worden gebruikt om radiogolven te detecteren. De terahertz (THz) frequentieband (0,3 – 10 THz) met golflengtes van 1000 – 30 μm , zit tussen de millimeter- en infraroodgolven in. Waarnemingen in deze frequentieband geven veel unieke informatie die ons helpen om astronomische sleutelvragen te beantwoorden. Echter, de straling met een frequentie die hoger is dan 1 THz, supra-THz golven genaamd, wordt door de aardatmosfeer geabsorbeerd, vooral door waterdamp. Daarom worden observatoria voor deze frequentieband naar een grote hoogte boven aardoppervlak gebracht of ze worden de ruimte in gelanceerd.

Om informatie uit de THz straling te halen, is een gevoelige detector met een hoge spectrale resolutie nodig. Heterodyne detectie kan een zeer hoge spectrale resolutie bereiken door het mixen van een signaal uit de ruimte met een zelf opgewekt signaal uit een lokale oscillator (LO). De lokale oscillator werkt als referentie om samen met het signaal uit de ruimte een verschilsignaal met een microgolf-frequentie te genereren. In het microgolf-frequentiegebied zijn lage-ruisversterkers en spectrometers beschikbaar om de signalen te verwerken. Heterodyne ontvangers, gebaseerd op heterodyne bolometers (HEB) mixers zijn de gevoeligste detectoren in het supra-THz frequentiegebied. Daarom worden HEB's in telescopen in de vorm van single pixel en als arrays gebruikt om THz-straling uit de ruimte te detecteren. Omdat de levensduur van ruimteobservatoria beperkt is door budget, brandstof, en stralingsschade door kosmische straling, is het van belang om zoveel mogelijk te onderzoeken binnen de beperkte observatietijd. Vergelijken met een enkelvoudige ontvanger, is de efficiëntie van een array ontvanger hoger, proportioneel met het aantal pixels.

In mijn proefschrift beschrijf ik een aantal sleuteltechnologieën voor de ontwikkeling van heterodyne array ontvangers gebaseerd op HEB mixers. Daarnaast heb ik een HEB mixer onderzocht, gemaakt van een nieuwe supergeleider (MgB_2), die anders is dan de gebruikelijke HEB mixers die bij een lagere temperatuur van 4K werken. De nieuwe HEB mixer werkt al bij een relatief hoge temperatuur (20K) en wordt gekoeld door een compacte, lage massa, lage dissipatie, space qualified 20K koeler. Dit kan een game changer zijn voor toekomstige observatoria. Bovendien bieden MgB_2 mixers een veel grotere verschilsignaal bandbreedte (≥ 10 GHz). Het is met mijn proefschrift gelukt om significante vooruitgang op vier belangrijke vragen in moderne THz heterodyne techniek aan te wijzen, deze zijn beschreven in hoofdstukken 3 – 8.

Hoofdstuk 1 geeft een introductie over terahertz astronomie voor de wetenschappelijke motivatie van dit proefschrift, een overzicht van heterodyne detectie technieken en een introductie over op HEB gebaseerde heterodyne single pixel ontvangers en heterodyne array ontvangers. Hoofdstuk 2 geeft enige achtergrondinformatie over de in dit proefschrift beschreven componenten.

In hoofdstuk 3 beschrijf ik een optisch onderdeel dat ik heb ontwikkeld dat een ongedefinieerde laserbundel omvormt naar een ideale vorm — de Gaussische bundel. Het is een ver-infrarood filter bestaande uit twee back-to-back gemonteerde silicium lenzen, met een apertuur gedefinieerd op een dunne goudlaag er tussenin. Bij gebruik van het optische onderdeel op een quantum cascade laser (QCL) met een slechte bundelkwaliteit, kreeg ik een Gaussische bundel op de uitgang met een 30% transmissie efficiëntie — de verhouding tussen de energie na de uitgang en voor de ingang. Dit is nog steeds een significante efficiëntie gezien de intrinsieke transmissie van 72% van de twee back-to-back silicium lenzen zonder apertuur en ook rekening houdend met de slechte kwaliteit van de ingangsbundel. Zo'n bundelfilter is erg nuttig voor toekomstige heterodyne instrumenten voor hoge frequenties.

Hoofdstuk 4 en 5 behandelen twee studies over fourier- of fase-tralies voor het maken van meerdere bundels uit één laserbundel. Omdat het gebruik van een enkele laser voor iedere mixer in een array met meer dan enkele pixels niet realistisch is, is de combinatie van een laser met een fase-tralie een elegante en betaalbare benadering voor het maken van een LO array voor heterodyne array ontvangers. Hoofdstuk 4 toont een 9x9-pixel Fourier tralie, die een enkele QCL bundel in 81 bundels verdeelt, met een erg hoge efficiëntie, wat nog niet eerder in de literatuur is beschreven. Hoofdstuk 5 gaat over de bandbreedte van een 8-pixel fase-tralie voor de NASA missie Galactic/Xgalactic Ultra long duration balloon Spectroscopic Stratospheric THz Observatory (GUSTO) aan de hand van een simulatie. Het resultaat van dit werk heeft ook bruikbare informatie

opgeleverd voor het ontwerp van het Heterodyne Receiver for the Origins (HERO) instrument voor de voorgestelde Origins Space Telescope (OST).

Hoofdstuk 6 en 7 beschrijven een HEB mixer gebaseerd op een nieuwe supergeleidende MgB_2 dunne film, welke al werkt bij een hoge temperatuur (20K) en een grotere bandbreedte heeft dan de gebruikelijke NbN HEB mixers. De grote bandbreedte heeft een groot voordeel bij het detecteren van THz straling in het hogere deel van het THz frequentiegebied. De lage-ruis prestaties van een MgB_2 HEB mixer is voor de eerste keer gemeten bij 2,5 THz en 5,3 THz. Dus een verdere afname van de ruistemperatuur van MgB_2 HEB mixers is in de toekomst te verwachten. Het functioneren van een HEB bij een hogere temperatuur is bijzonder interessant en veelbelovend vanwege de beschikbaarheid van een compacte, lichte en weinig dissiperende, space qualified 20K koeler. Het gebruik van de 20K koeler zou revolutionair zijn en nieuwe kansen voor ruimteonderzoek mogelijk maken, zoals de volgende generatie van THz-observatoria met een aantal telescopen samen gebruikt als een interferometer in de ruimte.

Hoofdstuk 8 geeft een gedetailleerde concept- en ontwerpstudie van een 1000-pixel array ontvanger voor een observatieplatform, zoals de Stratospheric Observatory for Infrared Astronomy (SOFIA), en potentieel voor een toekomstig THz-ruimteobservatorium. Hoewel state-of-the-art heterodyne array ontvangers tot in de orde van 10 pixels bevatten, streven de gebruikers naar de bouw van grotere heterodyne array ontvangers. Het concept van een 1000-pixel heterodyne array ontvanger is door de Universiteit van Arizona en SRON Netherlands Institute for Space Research voorgesteld op de SOFIA workshop in 2020. In dit hoofdstuk beschrijf ik het ontwerp en de analyse van een 1000-pixel heterodyne array ontvanger, inclusief de focal plane array met een HEB array en een lens array, een LO array gegenereerd door een QCL en een fase tralie, IF keten, en spectrometers. De IF keten versterkt het signaal en de spectrometers lezen het frequentie spectrum van het signaal. Dit hoofdstuk is een referentie voor het bouwen van een grote heterodyne array ontvanger (~ 1000 pixel) voor een toekomstige THz telescoop.

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