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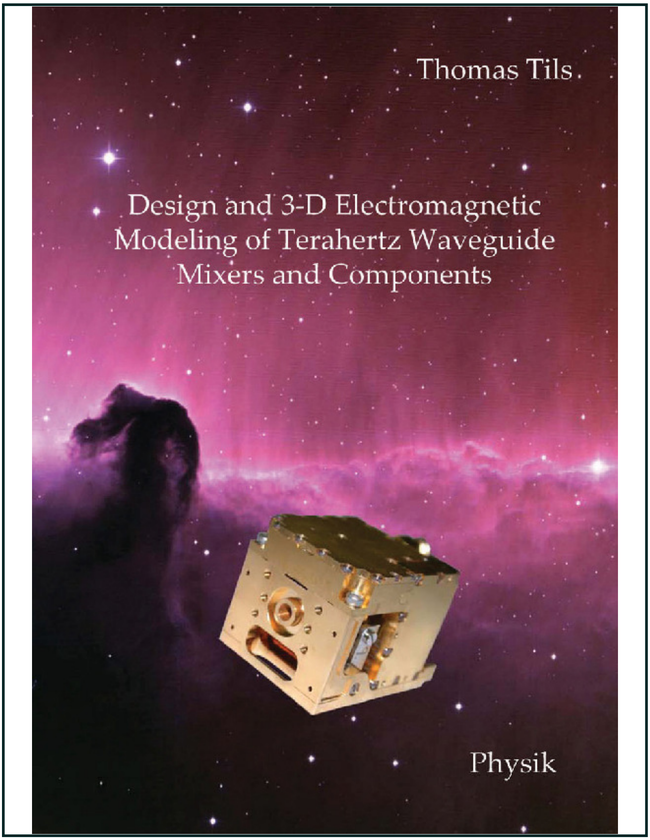
Design and 3-D Electromagnetic Modeling of Terahertz Waveguide Mixers and Components



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1 Introduction

1.1 Submillimeter and Terahertz Astronomy

Submm wavelength spectroscopic observations are an important cornerstone in studying the mechanisms that lead to star formation. High resolution spectroscopy with suitable instrumentation makes identification of molecules and atoms in our galaxy and in extragalactical objects of star and planet formations possible. The intensity of astronomical radiation in the focus of a radio telescope is very weak (<1 pW) and requires highly sensitive detectors.

A heterodyne instrument allows high resolution spectroscopy to detect radiation emitted at submm and shorter wavelengths while preserving the amplitude and phase information. The signal is superimposed with a Local Oscillator (LO) signal and converted in a mixing device to a two orders of magnitude lower frequency, the Intermediate Frequency (IF) of a few Gigahertz (GHz). This IF signal is amplified significantly and analyzed with a spectrometer. For example the HIFI spectrometer offers a resulotion of ≈ 1 MHz with a bandwidth of 4 GHz, equivalent to $\cong 0.4$ km/s resolution at 700 GHz and $\cong 1700$ km/s bandwidth.

Thanks to the extremely sharp non-linear I-V characteristic, Superconductor-Insulator-Superconductor (SIS) [1] devices are the ideal choice as mixing device up to a material dependent frequency of currently 1.2 THz. As highly sensitive mixers they provide quantum limited performance. For higher frequencies (up to 3 THz) superconducting Hot-Electron-Bolometers (HEB) [2, 3] are presently the best devices for heterodyne mixing.

The atmospheric absorption limits the possibilities of ground-based observations at submm wavelengths, because molecules in the earth's atmosphere (predominantly water) absorb the extraterrestrial radiation. Only a few atmospheric windows allow ground-based observations up to 500 GHz, around 660 GHz, from 800 to 880 GHz and around 1.4 THz. Locations with an atmosphere with a low water vapour content on earth are found in the Atacama desert in Chile (APEX, and later on ALMA), on the Mauna Kea (Hawaii), generally inside Antarctica (i.e. the now decommissioned AST/RO at the South Pole station), but also at KOSMA's own observatory on the Gornergrat (Zermatt, Switzerland). Ground-based observatories can utilize large mirrors and give the possibility of interferometric observations, e.g. the Atacama Large Millimeter Array (ALMA) in Chile.

Observations at higher frequencies than 1.5 THz are not possible with ground-based telescopes. To overcome these limitations, an airborne (SOFIA [4]) and a space telescope (Herschel) as well as balloon missions are planned. These and additional projects are discussed in Section 1.3. The advantages of an airborne telescope against ground-based telescopes are low atmospheric absorption and it allows observation from every point on earth, i.e. the southern and the northern sky can be observed with the same instrument. It offers the opportunity to change the instrumentation and operate with state-of-the-art technology, which is not possible in case of a space-borne observatory. On the other hand, with a space telescope H_2O can be studied in astronomical important environments, because there is still much absorption even at the cruising altitude of SOFIA (12 - 14 km).

With the remarkable sensitivity improvements of mixing devices for submm receivers realized in the past 10-15 years, the coupling of the mixing device to the antenna beam has become a determining factor for the sensitivity and functionality of these receivers.

Upcoming heterodyne projects require mixers with high coupling efficiency over a broad frequency range. Generally speaking, the mixing device itself can be thought as a device with quantum limited performance and all additional losses, i.e. increased levels of mixer noise temperature above the quantum limit are due to coupling losses within the mixer. Principally the mixing device RF environment can be either of a open structure[1] or of a waveguide environment kind. Although both types can deliver similar sensitivity, waveguide mixers bear the significant advantage of providing a well defined beam to the telescope. Therefore waveguide mixers are considered advantageous wherever the manufacturing of the waveguide features is technologically possible. KOSMA plays a major role pushing the limits of waveguide technology. Currently this is set to 2 THz for the SOFIA/GREAT instrument (Section 1.3.2).

Waveguide mixers are well established and successfully applied in astronomical receivers for mm and submm operation. Today's challenges are the very broadband RF and IF frequency bandwidths, extension of the technology to THz frequencies (the waveguide feature sizes scale inversely with frequency) and integration of enhanced mixer technologies such as sideband separation and balanced

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[1] Open structure mixers use planar antennas combined with a lens for signal coupling.

mixers.

Section 1.2 introduces the principle setup of a waveguide mixer, a schematical drawing of a waveguide mixer is shown in Figure 1.1. In Section 1.3 the heterodyne projects which are the motivation of this thesis are summarized and Section 1.4 gives an overview of the following chapters.

1.2 Mixer Technology

Coupling the signal to a heterodyne mixing element can be accomplished in several ways. One option is an open structure mixer. There the free space wave is focused by a quasioptical lens to the device. They are often used at frequencies above 1 THz for technical and practical reasons [5, 6]. The 2-D structure of a planar antenna (e.g. spiral or double-slot) can be modeled for a high fractional bandwidth and the quasioptical lens antenna is comparatively easy to fabricate. On the other hand, the alignment of the lens with respect to the antenna is very critical and has a large influence on the beam characteristics of the quasioptical mixer [5].

The second method is the coupling via waveguides. Waveguide mixers offer 95% - 98% coupling to the Gaussian fundamental mode in free space via corrugated horn antennas. For both mixer types the superposition of the RF signal with the local oscillator (LO) signal is typically done outside of the mixer itself, in the simplest case with a beamsplitter[2].

A schematic of a waveguide mixer is shown in Figure 1.1. After superposition of the RF with the LO signal, the free space wave is transformed to a guided wave, i.e. to a waveguide mode. This mode then is transformed via a waveguide probe antenna to a stripline mode which feeds the signal to the mixing device. The waveguide probe is implemented on a substrate together with the mixing device. The stripline on the device provides RF choke function and on one end the mixing device's IF signal is coupled out to a coaxial connector. The strip line is connected with a bond wire to a connector for IF signal out-coupling.

In contrast to a quasioptical mixer, waveguide mixers are intrinsically closed, i.e. the device is completely covered by metal, except for the feed horn waveguide. Inside a waveguide, only signals with a frequency above the cut-off frequency of the waveguide can propagate. Hence a waveguide mixer is less sensitive against low-frequency electromagnetic disturbances. This is an important issue e.g. for the

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[2] For example a mylar foil with ≈95% signal transmission and ≈5% reflection.

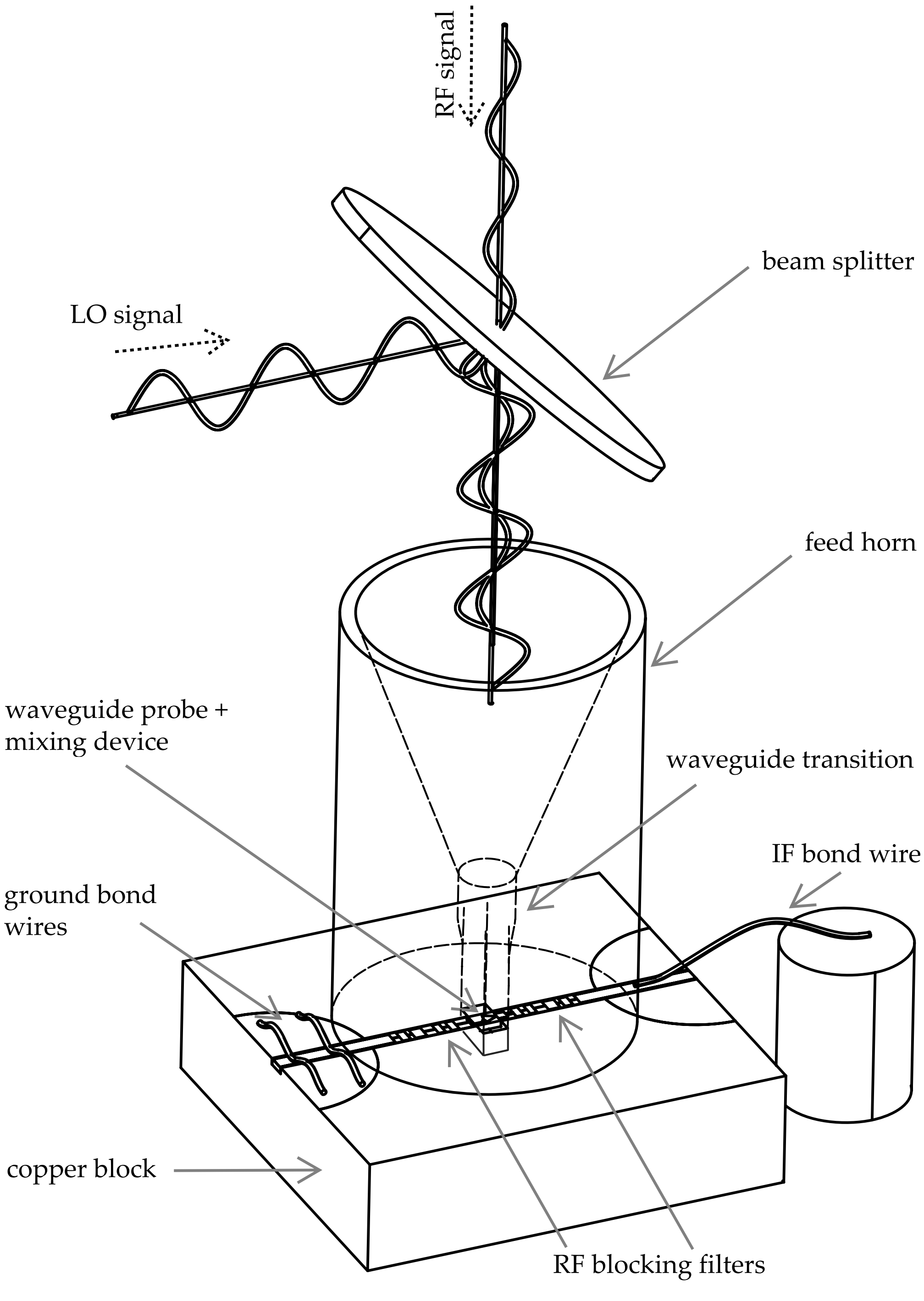

Fig. 1.1: Schematic of a waveguide mixer. The RF signal is superimposed with a LO signal with a beam splitter. The signal is coupled via a feed horn to a waveguide. A waveguide probe transforms the waveguide mode to a stripline mode which is coupled to the mixing device. The resulting IF signal is coupled out via a stripline (that also has the function of a RF blocking filter) and a bond wire to a coaxial connector. (Dimensions not to scale, for a scaled version see Figure 3.1, p. 44.)

HIFI mixers which have very tight specifications for electromagnetic susceptibility and electromagnetic interference [7].

1.3 Heterodyne Projects with Contributions in this Thesis

This thesis work contributes to several of KOSMA's current heterodyne receiver projects. Most notably it includes the waveguide RF design of the Band 2 mixer for the Herschel/HIFI instrument. The development for HIFI is adapted to design and optimize waveguide probes for other projects. Each project has its own design requirements, depending mainly on the RF frequency (bandwidth) and the type of mixing device. The following section gives an overview with short descriptions of the most recent projects.

1.3.1 HIFI

The Heterodyne Instrument for the Far-Infrared (HIFI) is one of three instruments of the Herschel Space Observatory (HSO). The Herschel Telescope (Figure 1.2) has a 3.5 m main reflector and covers the frequency range from 0.5 to 1.9 THz. The launch is planned for 2008 together with Planck[3].

HIFI covers the range from 480 to 1250 GHz with SIS mixers and from 1410 to 1910 GHz with Hot Electron Bolometer mixers. The Superconductor - Insulator - Superconductor mixer Band 2 (636 - 802 GHz) is one of the two contributions of KOSMA. As a mixing device, a Nb-AlOx-Nb SIS junction embedded into a NbTiN-SiO_2-Nb integrated tuning structure circuit is used [8, 9, 10]. Design, optimization and measurement of the waveguide probe, the RF filters and the waveguide environment of this HIFI Band 2 mixer is one of the main topics of this thesis and is described in Section 3.9. The principal design challenge of the Band 2 mixer is the very high fractional frequency bandwidth which can only be achieved by a novel probe design, especially since a low probe impedance is needed to accommodate large SIS junction areas, needed to maximize the device fabrication yield. In addition, simulations and measurements of the horn antennas and investigations of the very critical horn alignment are presented (Section 4.5.2).

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[3] Planck is an ESA (ESA is the abbreviation of "European Space Agency") mission to map the anisotropies of the cosmic microwave background. Both satellites will orbit around the second Lagrangian point (L2), i.e. on a line behind the earth-moon system as seen from the sun.

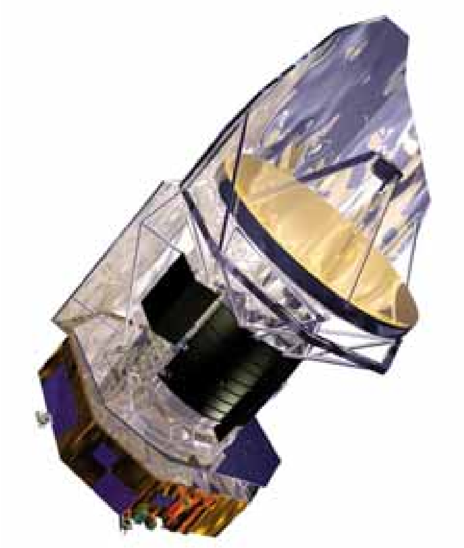

Fig. 1.2: Illustration of the Herschel space observatory.

The 4-8 GHz IF signal is analyzed by two types of spectrometers provided for HIFI, an Acousto-Optic Spectrometer (AOS) from KOSMA and an autocorrelator.

The two other instruments, the Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging REceiver (SPIRE) are high sensitivity cameras and low resolution spectrometers (60 - 210 μm and 200 - 670 μm).

The astronomical goals of HIFI are the observation of interstellar matter, in particular the high-resolution spectroscopy of gas within these regions, both in our local as well as in other galaxies. Herschel will provide unprecedented sensitivity for H_2O and C^+ observations. H_2O can exclusively be observed from space because the earth atmosphere absorbs this radiation. Together with the OI 63 μm (GREAT receiver) the C^+ 158 μm line is one of the major cooling lines of warm star forming regions. Knowledge of their precise intensity is crucial for understanding the star formation processes. Due to the lack of atmospheric interference, Herschel can also perform an unobstructed line survey covering the range of all its frequency bands. In addition, Herschel will target the outer planets of our solar system and study their atmospheric composition.

1.3.2 GREAT for SOFIA

The German Receiver for Astronomy at Terahertz frequencies (GREAT [11]) is one of eight 1st generation instruments for the Stratospheric Observatory for Infrared Astronomy (SOFIA). The SOFIA telescope consists of a parabolic 2.7 m mirror which is mounted in a modified Boeing 747SP airplane. SOFIA is a bilateral joint venture between NASA[4]) United States of America and the German Aerospace Center (DLR[5]). The start of operation is planned for 2007 with 20 year lifetime, the operating altitude is 12 to 14 km. The wavelength range covered by SOFIA will be 0.3 - 1600 μm.

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[4] NASA is the abbreviation of "National Aeronautics and Space Administration".

[5] DLR is the abbreviation of "Deutsches Zentrum für Luft- und Raumfahrt".

Fig. 1.3: Model of SOFIA.

The dual-channel heterodyne instrument GREAT is subdivided into three frequency bands (1.6 - 1.9 THz, 2.4 - 2.7 THz and 4.6 - 4.8 THz). Two of them can be used simultaneously in orthogonal polarizations. The heterodyne mixers and the receiver optics for the two low frequency bands are being developed by KOSMA. The science goal in the lowest frequency band is the observation of the C^+ fine-structure transition at 158 μm. A superconducting Hot Electron Bolometer on a 2 μm silicon nitride membrane is used as mixer device [12] and the mixer is carried out in waveguide technology. As part of this thesis, the waveguide environment for the 1.6 - 1.9 THz mixer has been developed (Section 3.11). A novel smooth-walled horn is used for the signal coupling from the mixer to the telescope optics. Measurements on a scaled version of this horn that were performed at 840 GHz to verify the design are described in Section 4.7.

1.3.3 CONDOR

The CO N^+ Deuterium Observations Receiver (CONDOR) is a receiver of the DFG[6] - Nachwuchsgruppe at KOSMA. It covers the frequency range from 1.25 to 1.5 THz and has a modular design for astronomical observations on the Atacama Pathfinder EXperiment (APEX) and SOFIA. APEX is a prototype antenna for the Atacama Large Millimeter Array (ALMA) with 12 m diameter located in Chile and operated by the MPIfR[7] in Bonn. CONDOR has observed at APEX in November 2005, a second mission is planned for 2006.

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[6] DFG is the abbreviation of "Deutsche Forschungsgemeinschaft".

[7] MPIfR is the abbreviation "Max Planck Institut für Radioastronomie".


Fig. 1.4: The Atacama Pathfinder EXperiment (APEX).

Scientific goals of CONDOR are measurements of rotational transitions of the CO molecule in star forming regions at 1.267, 1.382 and 1.497 THz, the detection of the fine structure line of N^+ in ionized components of the ISM (1.461 THz) and para-H_2D^+ in dense star-forming cores at 1.37 THz. The CO line at 1.497 THz was successfully observed in 2005 at the APEX telescope [13].

The waveguide mixer environment, designed within this thesis work, is similar to this of the SOFIA/GREAT mixer (Section 3.11).

1.3.4 RadioNet

In addition to the efforts to develop waveguide mixers at THz frequencies, novel heterodyne projects use advanced mixer designs, i.e. sideband separation or balanced mixers. This kind of mixers can be realized very compactly in waveguide technology.

RadioNet [14] is a promotional program for advanced radio astronomy in Europe. One of several activities is the Joint Research Activity (JRA) "Advanced Millimetre and Submillimetre Technology for Astronomical Research" (AMSTAR) [15].

The contribution of KOSMA to AMSTAR is a prototype of a sideband separation SIS mixer for array applications, initially for operating at 345 GHz but with the option to scale the designed components for application at higher frequencies. In the focus of this thesis the RF components for this project are designed by utilizing the 3-D simulation software. The key component, a 90° branch-line directional waveguide coupler, has been manufactured as a prototype and was characterized by measurements at the operating frequency (Chapter 5). Also, designs for necessary waveguide LO couplers and waveguide loads are presented.

1.4 Thesis Overview

The aim of this thesis is the design, optimization and characterization of waveguide mixers and waveguide components for several receiver projects. The work presented is mostly based on 3-D electromagnetic field simulation with the software tool Microwave Studio® from Computer Simulation Technology (CST). As will be shown, the software allows a much faster optimization loop between design and performance of the waveguide components. Due to the dimensions of the fabricated submm and THz structures, fabrication tolerances are important to consider. Therefore verification measurements are crucial and will be described in detail.

This thesis is arranged as following:

Chapter 2 gives a brief introduction about the SIS and HEB mixer device physics. Then the properties of waveguides, in particular the waveguide losses are discussed. In a general view the characterization of microwave components by the scattering matrix is discussed and then described in detail for waveguide mixer RF environments. Two simplified probe types are analyzed analytically and an introduction to the 3-D electromagnetic simulation software is given.

Chapter 3 presents the waveguide mixer technology and the mixer design of the HIFI Band 2 mixer. The dimensioning of the waveguides and substrates is discussed as well as the requirements on the waveguide probe and the RF blocking filter. Then the implementation of the 3-D simulation for designing and optimizing waveguide mixers is presented and the basics of the Fourier Transform Spectrometer which is used for design verification are given. After the waveguide itself, the waveguide probes, which act as antennas coupling the waveguide field to the microstrip modes of the devices, are individually discussed in detail for each mixer design. These are, foremost, the HIFI Band 2 mixer (636 - 802 GHz), followed by the AMSTAR mixer (≈345 GHz), the HEB mixers for CONDOR (1.3 - 1.5 THz) and GREAT (1.7 - 1.95 THz) as well as the two SMART mixer bands (440 - 495 GHz and 795 - 885 GHz) and the MIRA mixer (≈278 GHz). A detailed analysis of fabrication tolerances based on the 3-D simulation is performed for the example of the HIFI Band 2 mixer design. The chapter closes with an analysis of measured surface roughness of waveguide components manufactured by different methods.

Chapter 4 is focused on the analysis of waveguide horn antennas. Common feed horn types are introduced and principle considerations of the functionality are given. Next the simulation methods are explained, here focussing on the antenna simulation. As the manufacturing process of the feed horn's manufacturer ini-