論文の内容の要旨

論文題目

Design and Analysis of Optics in Terahertz Receivers for Radio Astronomy
（電波天文用テラヘルツ受信機における光学系の設計と解析）

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Radio astronomy at Terahertz frequencies (0.1 – 10 THz) is a relatively new branch of astronomy powered by the development of receiver technologies at these traditionally unexplored wavelengths which lie between radio frequencies and the far infrared. The difficulty in applying radio or optical techniques in this range has postponed astronomical observations until recently. A rapid technological development powered by a renewed interest in applications in this band has allowed the development of THz receivers to be used for astronomy and astrophysics.

Astronomical observations at these frequencies are critical to understand star and planet formation in our Galaxy and extragalaxies, interstellar chemistry, and magnetic fields in space, among others. Black body radiation from the cold interstellar gas peaks at these frequencies, which makes them very important for continuum observations. The THz range is also especially rich in rotational spectral lines of fundamental molecules present in the interstellar medium. The careful study of detected lines allows characterizing the composition, red-shift and chemical and physical characteristics of astronomical objects. The detection of the polarization of radiation coming from astronomical sources is also critical to improve our understanding on magnetic fields in space and its possible influence in star formation processes.

The development of very sensitive receivers at frequencies around 1 THz is very recent, which makes this spectral region very interesting for astronomy. Improvements in receiver technology directly impact on our capabilities to study astronomical objects. Improvements in sensitivities allow detecting fainter objects. Improvements in optical efficiencies allow shorter acquisition times and deeper observations with a given time. Improvements in polarization discrimination allow better characterization of magnetic fields.

Receiver radio-frequency (RF) input optics is one of the key elements of receivers for radio astronomy at THz frequencies. It couples the energy collected by the usually large telescope antenna into the tiny ultra-sensitive detectors required by radio astronomy. At THz frequencies, optics also provides an efficient solution for local oscillator (LO) injection in heterodyne receivers. Quasi-optics provide an elegant and simple theory for the analysis of this kind of optics. In radio astronomy applications, optics is usually located completely or partly within the confined space of a cryostat, since detectors are usually cooled down at temperatures near 0 K in order to improve sensitivity.

This thesis describes the design, analysis, and optimization of optics for several receivers to be used for radio astronomy research in the ALMA (Atacama Large Millimeter/sub-millimeter Array) and ASTE (Atacama Sub-millimeter Telescope Experiment) telescopes. The focus of this thesis is the analysis of some recently discovered receiver performance degradations due to fabrication and alignment tolerances of optical components, which are comparable to their small size, and due to the effect of the operating environment. The understanding of these degradations becomes critical to improve performance as detector performance is currently approaching physical limits. The receiver cross-polarization performance, basic for observations of magnetic fields in space, is also studied in detail.

LO injection optics aims at providing a stable LO signal to the mixing device. The more stable the signal, the more stable the operation of the receiver is. This translates into more repeatable astronomical measurements and the possibility to extend single-observation times. In this thesis, a horn-to-horn power transmission system has been proposed and useful design equations have been derived. The concept has been proven by careful measurements and used for the ALMA band 10 receiver (787-950 GHz). A similar system has been successfully used in the measurement of the beam patterns of a 900-GHz receiver based on HEB mixers developed at the University of Tokyo. Additionally, simple quasi-optical attenuators based on beam truncation have been design, fabricated and used on ALMA band 10 receivers. These attenuators have been useful to increase the sensitivity of the receiver by reducing its noise temperature.

In the case of RF optics, the optical systems of the two previous receivers have been carefully analyzed theoretically and characterized in the laboratory. A new tolerance analysis method has been proposed to consider the effect of fabrication and alignment tolerances in optics at THz frequencies. The application to ALMA band 10 has been useful to determine the expected performance variations for each one of the 66 cartridges (+7 spares) to be used in ALMA. The analysis results show good agreement with the measurement results of the 60 cartridges manufactured and tested so far. The application to the HEB-mixer receiver has been useful to identify a defective component, which will be replaced in the future. The receiver performance is expected to be enhanced after this replacement, with the consequent improvement in astronomical observation capabilities.

When the ALMA band 10 optics was first used within a cryostat, optical performance was greatly degraded with respect to room-temperature operation. Reflections on the cryostat infrared filters and window have been identified as the cause of this degradation and solutions have been proposed. This has allowed an average aperture efficiency improvement as large as 2.5 % at some frequencies. Typical beams before and after the optics modification proposed in this thesis are shown in figure 1.

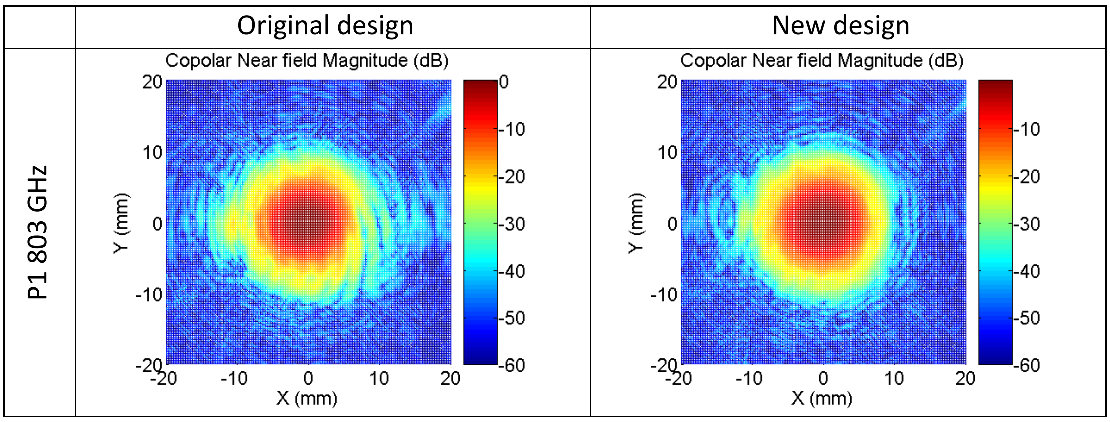

Figure 1. Comparison of co-polarization beam patterns measured for polarization P1 of ALMA band 10 cartridge #6 using the original and the improved ALMA band 10 optics design

A new method to estimate the total cross-polar performance of a receiver has been developed and successfully applied to the analysis of ALMA band 4 (125-163 GHz) and band 10 optics. This method is based on the modeling by Gaussian modes of the cross-polarization contributions generated by the different components in a receiver. It aims at obtaining the phases with which different components combine. It provides clear indications on how to design robust optics in terms of cross-polarization.

Finally, the frequency dependence of the ALMA band 4 cross-polarization performance has been analyzed by careful electromagnetic analysis. The dielectric loading of the horn antenna has been identified as the most likely cause of the cross-polarization degradation measured at some frequencies.

The new analysis methods and solutions proposed along this thesis are of interest for most astronomical receivers for observations at millimeter and sub-millimeter wavelengths. The results presented in this thesis have been applied to the ALMA band 10 receiver and to the University of Tokyo HEB receiver and have contributed and/or are expected to contribute to improve the performance of both receivers. In particular, this work contributed the unprecedented receiver performance of the ALMA band 10 receiver. In turn, this means enhanced observation capabilities and the possibility of performing more and better astronomical observations in the relatively unexplored 900-GHz region. As an example of this improvement, the average improvement of measured aperture efficiency (ability of a receiver to feed the radiation coming from the secondary into the detector) is presented in Table I.

Table I. Improvement in aperture efficiency of the ALMA band 10 receiver (787 - 950 GHz) for orthogonal linear polarizations P0 and P1 after applying the research results in this thesis

	P0 804 GHz	P1 804 GHz	P0 879 GHz	P1 879 GHz	P0 943 GHz	P1 943 GHz
Initial design	84.26 %	83.52 %	84.13 %	84.63 %	85.63 %	85.69 %
After this thesis	86.23 %	86.20 %	86.16 %	86.21 %	86.04 %	85.94 %
Improvement	1.97 %	2.68 %	2.03 %	1.58 %	0.41 %	0.25 %

Additionally, the careful research on cross-polarization has allowed understanding the limitations of the ALMA band 4 receiver in terms of polarization discrimination. An improvement of the polarization discrimination capability of this receiver is difficult due to different constraints. However, the results of this thesis should be helpful to improve our understanding on cross-polarization generation in receivers and to not making the same mistakes in future receivers. Therefore, these results will be useful to understand how to design receivers which can measure the polarization of the incoming signal with high accuracy. Such a performance will open a new field in astronomy and astrophysics by allowing us to measure the magnetic field and its distribution in space with unprecedented sensitivity. The role of magnetic fields in space is still poorly understood and an outstanding problem which requires new receiver developments. Polarization discrimination performance such as that of the ALMA band 10 receiver is useful to tackle this problem properly.