A Testbed for Modeling Validation and Characterization of Quasi-optical Elements in Microwave Receivers

L. Lamagna1,2 · M. Basilicata1 · A. Occhiuzzi1 · F. Columbro1,2 · A. Coppolecchia1,2 · G. D’Alessandro1,2 · P. de Bernardis1,2 · S. Masi1,2 · L. Mele1,2 · A. Paiella1,2 · G. Pisano1

Received: 31 October 2021 / Accepted: 8 August 2022 / Published online: 5 September 2022 © The Author(s) 2022

Abstract
We describe the setup for the broadband millimeter/submillimeter characterization of the quasi-optical elements and the dielectric materials commonly used in microwave receivers operated in microwave astronomy. The setup is made of a large aperture (100 mm) Fourier transform spectrometer coupled to a transition edge superconducting detector. The system has been assembled and characterized in different configurations and operation modes for the acquisition of interferograms from various kinds of samples. After the initial test runs, the configuration is now being updated to ensure a broader range of measurements, including reflectance and scattering. We plan to first use this testbed for the characterization of the dielectric materials used in the LSPE/SWIPE experiment, devoted to the study the polarization of the Cosmic Microwave Background.

Keywords Cosmic microwave background · B–modes · Quasi-optical systems · Fourier transform spectroscopy

1 Introduction

A dedicated testbed has been developed and verified for sensitivity and systematics in order to provide consistent performance in the characterization of materials and quasi-optical subsystems of common application in microwave detection. The main driver for the sensitivity and accuracy requirements of this testbed is its application in laboratory testing for observational cosmology experiments. The measurement of the polarization of the Cosmic Microwave Background (CMB) radiation is one
of the current frontiers in cosmology. In particular, the detection of the primordial divergence-free component of the polarization field, the B-mode, is at the moment the most promising technique to probe the inflationary theory which describes the very early evolution of the Universe.

SWIPE [1, 2] is a microwave polarimeter devoted to the search of such tiny curl-like features in the linear polarization pattern of the CMB anisotropies, as a part of the Large Scale Polarization Explorer (LSPE) project. Given the ambitious observational target, every subsystem in the receiver must be carefully modeled and tested to assess its compliance with the tight requirements on calibration and systematics. The testbed described in this paper was therefore designed and verified in view of the quasi-optical modeling validation activity for SWIPE or other receivers of the current generation.

2 The SWIPE Instrument

The uniqueness of SWIPE consists of 3 main features:

*Operation from the stratosphere:* observations will be performed in a long duration flight (15 days) during the Arctic night. This ensures a large (Hemisphere, achieved by spinning the payload around the local zenith axis at \(\sim 0.7\text{s}^{-1}\) while stepping altitude between 35° and 55°, in combination with Earth rotation. The stratospheric environment will ensure a limited impact from the atmospheric emission on detector power loading and a generally low contribution of the atmospheric fluctuations to the noise budget, especially in the highest frequency bands.

*A cryogenic telescope with multi-moded detectors:* a single Ultra High Molecular Weight Polyethylene [3] lens, cooled down to 2K, illuminates two focal planes through a large tilted polarizer acting as a polarization splitter. Each transition edge detector is coupled to the 480mm aperture through a multi-moded horn/waveguide assembly, and its absorber is designed to couple very efficiently tens of radiation modes [4]. This design is applied to the three bands filling the focal planes, centered at 145, 210 and 240 GHz with 30%, 20% and 10% bandwidth, respectively. The total field of view is \(\sim 20^\circ\), with an 85’ FWHM resolution per multi-moded pixel (163 pixels per polarization) [2].

*Active polarization modulation:* the modulation of the incoming polarized signal is performed with a dedicated cryogenic subsystem, based on a superconductive magnetic bearing which spins a Half Wave Plate at 0.5revolutions/s (2Hz polarization modulation) [5]. While adding hardware complexity and the need to perform a dedicated assessment of its related systematics, this subsystem ensures excellent control of instrumental polarization issues [6]. This solution is shared by many current and next generation B-mode experiments, including QUBIC [7] and LiteBIRD [8].

Through these features, SWIPE is expected to achieve a final Q,U map sensitivity of 10, 17 and 34\(\mu K_{\text{CMB}}\cdot\text{arcmin}\) in its three bands, and it aims at constraining a
tensor-to-scalar ratio of $r=0.03$ with $3\sigma$ significance in conjunction with its partner ground-based instrument, LSPE/STRIP [1].

3 Quasi-Optical Modeling

A number of existing numerical tools and methods have been used to model the performance of the SWIPE receiver. Among these, the Physical Optics solver of the GRASP/TICRATools\(^1\) suite has been used to model the telescope and to simulate its angular efficiency in the presence of the multi-moded horns, the optics encasing, the filter apertures, and the forebaffle. In addition, the Ansys HFSS\(^2\) package has been used to predict the behavior of multi-moded absorbers for the TES detectors and their coupling to the rest of the optical system. In order to validate the predictions and the assumptions performed in the optical modeling activity, a set of subsystem-level tests had to be carried out. Such activity has repeatedly provided support and inputs for more complex and accurate studies, especially when unexpected testing systematics had to be interpreted and addressed. One of the major recent achievements of such approach has been the modeling and characterization of the multi-moded horns of the SWIPE detectors [9]. We expect a robustly validated simulation effort to prove especially useful in assessing system-level performance and performing in-flight calibration and data analysis.

4 Testbed for Broadband Quasi-Optical Characterization

The optical bench for the quasi-optical tests is made of a Fourier Transform Spectrometer (FTS) based on the Martin–Puplett [10] optical scheme. One output port of the FTS is coupled to the detector through a three mirrors configuration meant for compactness and easy mechanical arrangement. In our system, wire grids are used as polarizers for the microwave radiation. The detector system is a self-consistent cryogenic Transition Edge Sensor (TES) cooled to 4K by means of a Pulse Tube Cooler model PT403RM by Cryomech. The PTC unit delivers a cooling power of 6W at the 65K stage and 220mW at 4K and it cools down the TES in $\sim$6 hours with no need for operator attendance after the obvious and standard preliminary steps (cryostat evacuation, coolant circuit activation, etc.). Once cooled to base temperature, the detector and the readout chain achieve a Noise Equivalent Power (NEP) of $2.5\text{pW}/\sqrt{\text{Hz}}$, measured at 80Hz but with a fairly flat frequency dependence in the 5Hz-700Hz range, ensuring the possibility to perform fast optical or electrical modulation of the signals with no significant impact on the system efficiency. The detector is coupled to free-space radiation by means of an F/3.5 conical horn antenna cooled to 4K and a broadband filtering chain based on low-pass edge (LPE) filters built by QMC Instruments, with a cutoff frequency at 1.5THz. Additional filtering for

\(^1\) [http://www.ticra.com](http://www.ticra.com).

\(^2\) [https://www.ansys.com/products/electronics/ansys-hfss](https://www.ansys.com/products/electronics/ansys-hfss).
loading mitigation and optical antialiasing is performed through additional low-pass filters arranged along the path from the FTS to the detector. Such filters are selected on the basis of the features and requirements of the specific tests. The moving roof-mirror of the FTS is mounted on a Physik Instrumente LS-180 translation stage with up to 508mm mechanical displacement. By design, the stage is arranged so that the zero-path-difference (ZPD) position of the FTS is 30mm away from one edge of the moving stage. This allows to collect single-sided interferograms with up to 2×470 mm optical path difference (OPD), corresponding to a maximum spectral resolution of 0.3 GHz. In the standard configuration one of the two input ports of the system is terminated through the room temperature, highly emissive Eccosorb HR-10 panel. The other port is coupled to the microwave radiation source. The thermal emission from the bulb of a mercury arc lamp is comparable to a ~5000K blackbody over a broad spectral range (from few tens of GHz up to a few THz), making this a bright source suitable for the characterization of a broad variety of quasi-optical filters and materials, even in the non-trivial condition of very low transmittance or reflectance values. Potential issues related to temporal instability from the source have been investigated through continuous monitoring of the power spectrum of the ZPD signal from the lamp. They are currently addressed by collecting individual interferograms with scanning times below the fluctuation timescales of the lamp (10s of minutes), by interleaving reference measurements in the sequence of collection of interferograms, or even by use of rapid-scanning in place of the step-and-integrate strategy, whenever the added high-frequency noise due to continuous motor operation is clearly separable from the optical signal in the frequency domain.

A picture of the test FTS and detector assembly is shown in Fig. 1.

The system can be remotely operated to collect interferograms with two different strategies:

– By optically modulating the source with a chopper, interferograms are collected by stepping the moving mirror position into discrete locations (which ultimately determine the effective bandwidth of the sampling) across the available range of OPDs, and demodulating the detector signal through a lock-in amplifier;

– By fast-scanning the available range of OPDs the total-power signal is sampled through an Analog-to-Digital converter and averaged over an arbitrary number of full-range runs of the moving mirror. Here, the sampling rate determines the maximum electrical bandwidth and, after conversion with the velocity of the moving stage, the useful range of optical frequencies.

Both techniques are broadly used in FTS spectroscopy and feature different strengths and drawbacks [11]. In our context, the possibility to switch between the two will be used as a redundancy test for instrument systematics and a tool for the validation of instrument modeling in the presence of unwanted or unexpected features in the data. The preliminary results reported below are entirely based on the step-and-integrate strategy, with a 35Hz modulation frequency, a 300ms time constant, an equivalent noise bandwidth of 120mHz and a 50μm mechanical step size over a maximum full OPD range of 30mm. All the samples under test are at room temperature.
Test Run of the System

Following assembly and optical alignment, the system has been used to perform basic tasks of sample characterization in the high and low signal regimes. Among these:

- the measurement of the refractive index and transmittance properties of different highly transmissive plastic slabs (high density polyethylene, ultra-high molecular weight polyethylene, polypropylene);
- the spectral characterization of transmittance of very lossy dielectric layers used as microwave absorbers (Eccosorb AN, Eccosorb HR, Eccosorb CR);
- the spectral transmittance of quasi-optical filters with cutoffs or passbands in the few hundred GHz region.

While none of the preliminary tests listed above was meant to be informative about unknown properties of the samples, they helped in highlighting the strengths and weaknesses of the current setup in view of more extreme applications, like the broadband spectrometry in the very low signal regime, e.g. due to surface scattering, or reflectance from absorbing dielectrics and high-loss metamaterial structures. In these cases, detected radiation can easily fall off to a fraction of percent of the power collected from the reference source in the absence of the sample. Precision
measurements of such properties, especially with polarized millimeter-wavelength radiation, are likely to be dominated by testbed systematics and by overall system stability. In order to perform an assessment of such issues in the low transmittance regime, we collected a number of broadband spectra of a 5-mm-thick Eccosorb HR-10 slab (with an average transmittance of \( \sim 1\% \) below 1THz), under controlled environmental and operating conditions. Basic statistics of the reconstructed transmittance in 10 GHz spectral bins, as a function of frequency and accumulated interferogram acquisition time, is reported in the left panel of Fig. 2. The plot shows that a signal-to-noise ratio above 3 can be achieved over a large portion of the 200–700 GHz spectral region within a reasonable effective measurement time, accumulated through repeated scans interleaved with short source-monitoring sessions to track the intrinsic temporal variation of the mercury arc lamp. This ensures the capability to characterize percent-level transmittance within individual one-day sessions with a typical precision at the level of 10% at the upper edge and better than 30% toward the lowest edge of the testbed bandpass. One such measurement is shown in the top-right panel of Fig. 2.

In order to improve the limit sensitivity at frequencies below \( \sim 200 \) GHz, further investigation of the system stability has been performed. An analysis of the noise power spectra of the detection chain with and without the illumination by the lamp
(bottom-right panel of Fig. 2) shows an excess fluctuation at low electrical frequencies. This impacts the effective NEP of the system over the minute-long timescales needed for optical characterization of the lowest frequencies (corresponding to spatially and temporally slow modulation in the interferogram signal). A direct characterization of the TES noise at those frequencies is consistent with the one reported by the supplier over an even larger bandwidth, so the excess fluctuation can be attributed to intrinsic brightness fluctuations in the lamp used as a source. Work is underway to improve the long-term stability of the source, both by re-designing the power supply for the mercury arc and by procuring a custom thermal noise source which features more stable (albeit less bright) emission for the low frequency domain.

6 Conclusions

We have described a testbed for transmittance and reflectance measurements up to 1 THz, featuring a Martin–Puplett Interferometer with a mercury arc thermal source, a cryogenic broadband detector and reconfigurable optical paths for sample characterization at variable incidence angles. The illustrated setup has been routinely characterized through different modes of operation. Test spectra were collected with an Eccosorb HR-10 sample to inspect the system capability to constrain transmittance or reflectance in the percent-level range, showing satisfactory performance (better than 30% precision) above 200 GHz and up to 800 GHz within typical one-day measurement sessions, matching most of the requirements for the characterization of filters and materials in the region of interest for millimeter-wave astronomy and CMB observations in particular. Work is underway to extend the setup capabilities in order to achieve the following goals.

– An actual performance which is dominated by detector noise even at frequencies below 200 GHz, where the drifting in the broadband source is the currently dominant cause of residual instability in the collected spectra.
– The capability to arrange samples to perform reflectance and scattering spectral measurements in two orthogonal linear polarizations, allowing a full reconstruction of the dielectric tensor of the materials under test. To this end, an updated relay optics to couple the FTS to the detector has been designed, built, and assembled (see a Fig. 3 for a sketch). Alignment and characterization are underway.
– The implementation of a cryogenically cooled sample holder to complement room-temperature measurements with selected configurations at temperatures around 4K, where most of the quasi-optical applications, including the SWIPE receiver, take place.
Fig. 3 Updated relay optics setup for the FTS output. Starting from the upper-right side of the figure, the beam form the interferometer passes through the output wire-grid polarizer (diagonal element, also shown in the picture in Fig. 1) and through the PM1, PM2, FM1 series of mirrors (replacing the M1-M2 couple of mirrors shown in Fig. 1) it is directed toward the sample under test SH. The reflected/scattered beam is then re-collected by the FM2, FM3, PM3 series of mirrors to be focused on the detector. The moving stages TS1, TS2 and RS1 allow to reconfigure the system to operate at different incidence and scattering angles.

Funding Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement. The fund was grant by (Agenzia Spaziale Italiana).

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