Optical Testing of the CAmbridge Emission Line Surveyor (CAMELS)

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Abstract— **The motivation for this work is to develop submillimeter wave and far-infrared imaging technology in which each detector in a focal plane is intrinsically capable of yielding detailed spectroscopic information.A first step towards this is the development of the CAMELS instrument, which will eventually be used to survey nearby galaxies at 3 mm with a spectral resolution, R = δλ/λ, of about 3000.The CAMELS instrument is based on the Microwave Kinetic Inductance Detector (MKID), operating at 100 mK, combined with an integrated filter bank design to provide 512 spectral channels between 103.0 and 114.7 GHz.In this work, we present the ongoing optical measurements of the CAMELS detectors, including dark tests and planned line source and gas cell tests.**

INTRODUCTION

On-chip spectrometers for the millimeter and submillimeter waveband have generated increasinginterest in the past few years. In these devices, each detector pixel consists of a filter bank feeding multiple detector devices that are multiplexed onto a single readout line. Several projects, such as DESHIMA [1], SuperSpec [2], X-Spec[3],andWSpec[4] have been proposed for the submillimeter and far-IR wavebands. CAMELS is an instrument operating ata wavelength of about 3 mm.The scientific motivation of the CAMELS project is to map the ^{12}CO(1-0) and ^{13}CO(1-0) line emission from local galaxies with redshift in the range of 0.05-0.13 (^{12}CO) and 0.003-0.961 (^{13}CO), providing information about the evolution of the molecular gas content in galaxies throughout the cosmic epochs It will also serve as a pathfinder instrument for investigating the use of integrated filterbank spectrometers for astronomical observations.

Fig. 1 is a system diagram of the CAMELS instrument. The top panel shows the layout of the optics, cryostat and readout electronicsThebottom panel is a schematic representation of the CAMELS detector chip. It consists of a pair of horn-coupled microstrip feedlines, carrying two orthogonal polarization signals. The feedlines are coupled to an integrated bank of narrow-band superconducting resonator filters that provide spectral selectivity. The power admitted by each spectral selection filter will be detected by microwave kinetic inductance detectors (MKIDs) through a millimetre-wave coupler. Finally, all the MKIDs will be readout via a microstrip line using frequency domain multiplexing. The top right panel of Fig.1 shows the frequency multiplexing readout system of the instrument. The details of this readout scheme were presented in [5]. Fig. 1 shows a single-pixel system, however the compact design of the spectrometer will allow packing a powerful multi-pixel spectrometer system on a focal plane.

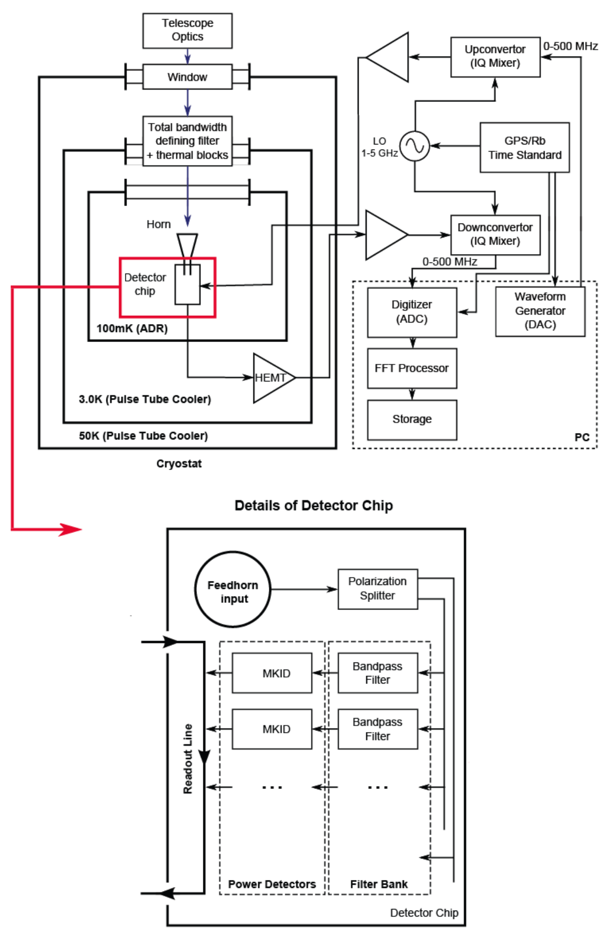

Fig. 1 System block diagram of the CAMELS instrument.

OPTICAL TESTS

Fig. 2 shows photos of a prototype CAMELS chip that is being tested to prove the technologies required for a full chip.The top panel shows the sample holder and the detector chip. The bottom panel shows the details of the detector chip, including the optical coupler (top right) and signal filter (bottom right).Key to the operation of the CAMELS devices is the use of β-Ta (Tc ~ 700mK) as a sensing material, which allows operation at millimeter-wavelengths.This is incorporated into the termination of quarter-wavelength NbN resonator for readout, similar to [6]. However, a novel optical coupler design must be used as both the milllimeter-wave and resonator line are microstrip. We use a scheme in which the millimetre-wave line overlaps the end of the resonator line, such that the β-Ta strip line of the resonator forms the ground plane of the signal line [5]. The test chips are to designed to verify this coupling scheme and allow investigation of loss and noise mechanisms for optimization of future designs.In addition, the signal is coupled into the chip via a planar antenna in the prototype devices, rather than a waveguide probe as planned for the final devices. The antenna is a centre-fed single slot design, which is illuminated from the underside of the detector chip through a window in the holder.

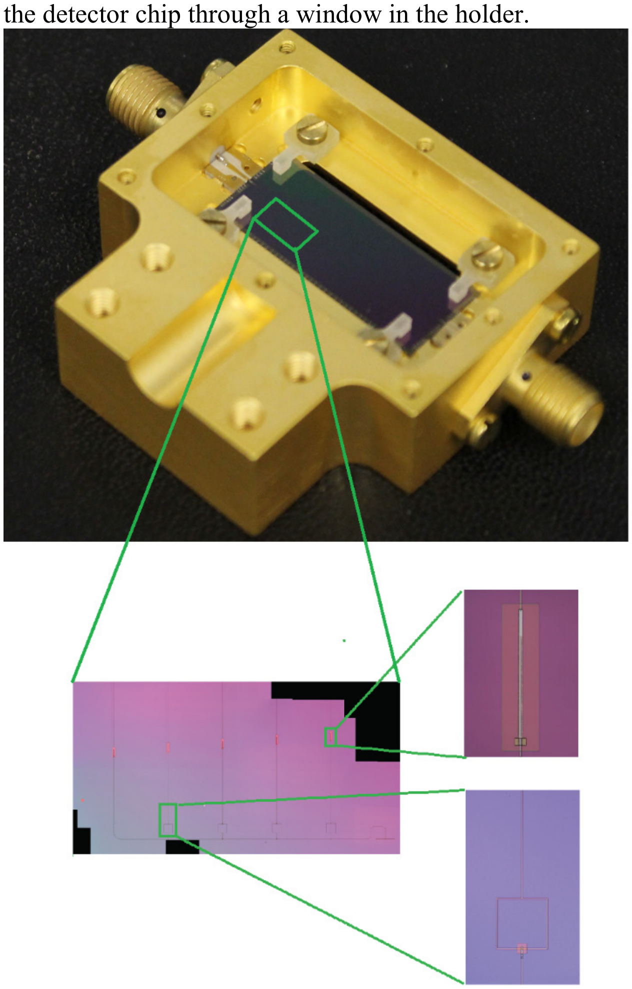

Fig. 2 CAMELS detector chip testing package.

A. *Dark tests*

In the dark tests, the detectors were sealed inside a metal jig to isolate them from the radiation of the surrounding environment. We performed frequency sweeps and bath temperature sweeps to measure the detector response using a vector network analyzer and a single-channel prototype of the broadband readout electronics which will eventually be used to read out an array of detectors multiplexed onto a single RF line. We fitted the resonant frequencies and quality factors of the resonators as a function of temperature. We have also studied the sources of noise in the detector and have determined the maximum readout power at which the onset of nonlinear behavior is observed.

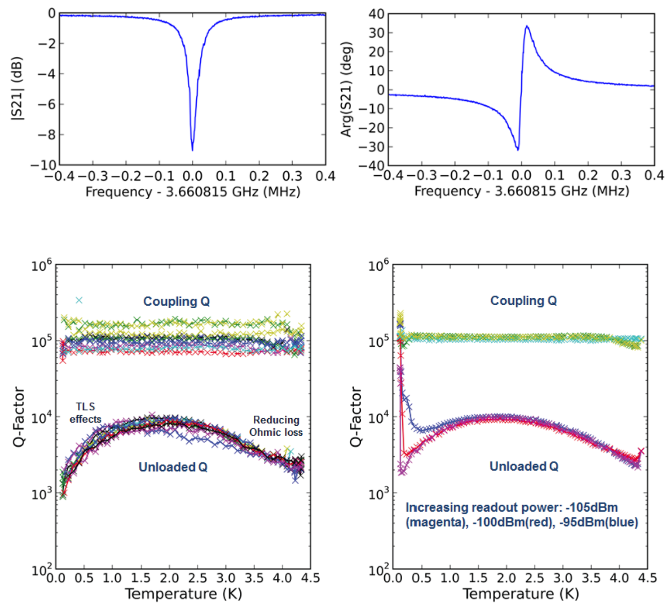

Fig. 3 CAMELS MKID resonator measurement results.

Fig.3 shows the measurement results of the CAMELS resonators on chip. Data are shown for a via-shorted NbN microstrip resonator without the millimetre-wave coupler. The top plots are the measured S_{21}magnitude and phase of a resonator centred at 3.660815 GHz. The bottom left panel shows the measured coupling quality factor Q_c and internal quality factor Q_i (unloaded Q) of different resonators at a low readout power. The variation in Q_c results from the varying resonant frequency for different resonators. The internal coupling factors drop at low temperature due to the two-level system effects in the dielectric and at high temperature due to the ohmic loss in the superconductor. The bottom right panel shows Q_c and Q_i of a resonator at different readout power level and at different temperature. At the operating temperature of100mK, we measured thepeak $Q_i$to be around 10^5.

B. *Line source measurement*

To measure the frequency-response of the integrated filters, we have developed a narrow-band cryogenic source that can be continuously tuned over the range 100-115 GHz. This line source is realized using a Pacific Millimeter Products harmonic mixer (FM model) mounted on the 4K plate as a cryogenic multiplier. We pump the multiplier with a <30 GHz signal produced by an external room-temperature synthesizer and coupled into the cryostat through a coaxial cable. The multiplied signal is then free-space coupled to the detectors on the 100mK stage, avoiding the need for a window or waveguide plumbing to low temperature. It also allows fast switching of the source power, which is useful for response time measurements and for distinguishing between optical response and thermal response from source loading, taking advantage of the different timescales of these processes. Initially, the power output of the line source wascalibrated in a 4K cryostat by transmission measurements to an external room-temperature detector (see Fig. 4), but we are also investigating in-situ monitoring at cryogenic temperatures via a directional coupler and cryogenic power detector. A good knowledge of the power output as a function of frequency is necessary to separate variations in detector response due to the filters from those due to variations in source.

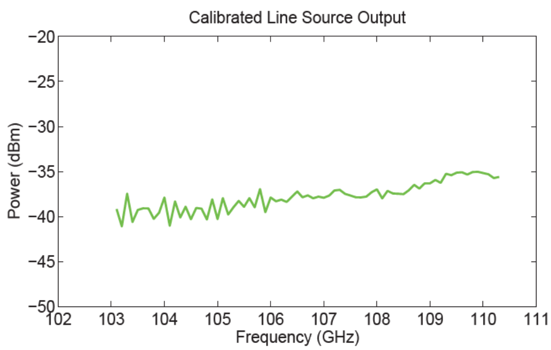

Fig. 4Line source output that is calibrated from 103 GHz to 110 GHz.

C. Gas cell measurement

In order to demonstrate the telescope-readiness of the CAMELS instrument, we intend to carry out measurements of spectral emission lines in a gas cell mounted outside the instrument cryostat. A liquid nitrogen cooled 77K load placed behind the cell will provide a low brightness temperature background to the gas emission lines in the ambient temperature cell, realistically simulating a typical astronomical observation (particularly in terms of coupling to the telescope). The use of a naturally abundant mix of carbonyl sulphide (OCS) isotopologues in the gas cell will provide five spectral linesspread across the CAMELS band (see Fig. 5 for details).These will provide a wide range of line temperatures,with pressuretuneable line width to cover a few CAMELS channels.

Fig. 6 shows aCAD model of the CAMELS gas cell measurement set up. The gas cell is coupled to the detectors by an optical path consisting of a room temperature parabolic off-axis mirror; vacuum window of the cryostat; IR blocking filters mounted on 50K and 4K shields; a secondary parabolic mirror mounted on the 4K plate and a conical feedhorn mounted on the detector package at the 100mK Adiabatic Demagnetization Refrigerator (ADR) stage.

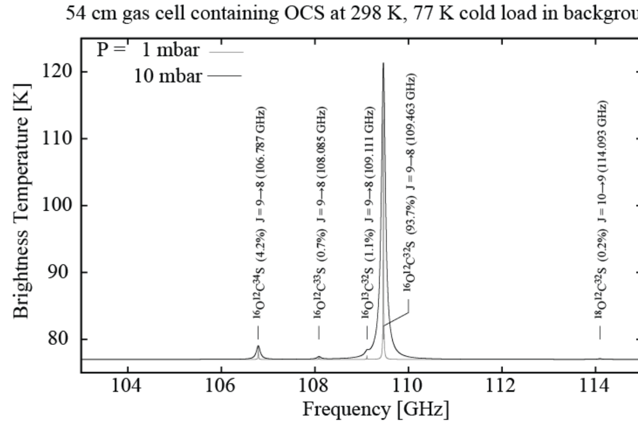

Fig. 5Five lines show up across the CAMELS band in asimulated OCS gas cell spectrumproduced with the*am* radiative transfer code [7].

CONCLUSIONS

Wehave presented the ongoing optical measurements of the CAMELS MKID detectors, including dark tests and planned measurement using a calibrated line source and an OCS gas cell.

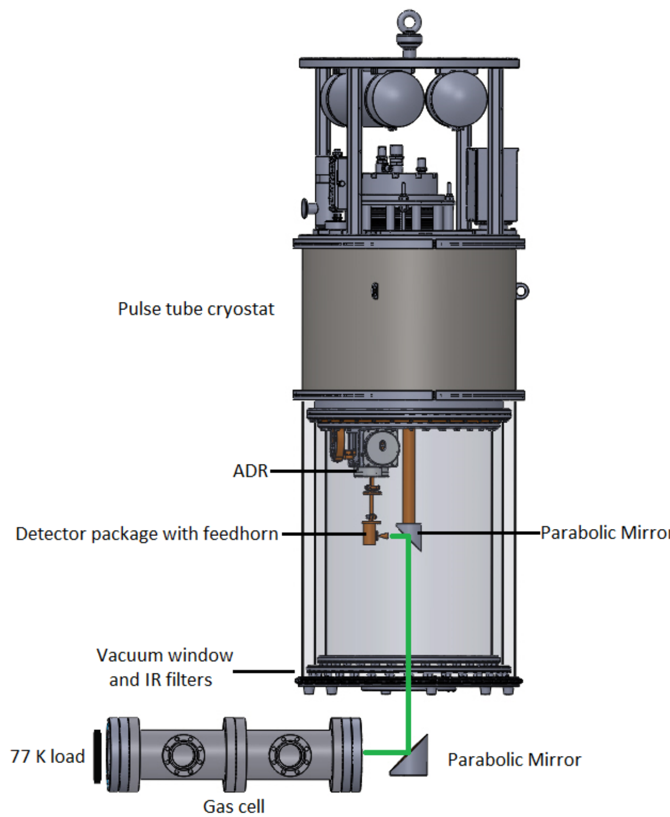

Fig. 6The CAD model of CAMELS gas cell measurement set up. Green line shows the optical path.

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