Progress on the CAmbridge Emission Line Surveyor (CAMELS)

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Abstract— **The aim of CAmbridge Emission Line Surveyor (CAMELS) is to provide an operational demonstration of an Integrated Filter Bank Spectrometer (IFBS) for mm-wave astronomy. The prototype will observe from 103-114.7 GHz, providing of order 500 channels with a spectral resolution of 3000. In this paper we discuss the design of the instrument and ongoing work towards its realisation. Fabrication of a first set of devices to verify the key technologies has recently been completed. We will present results from a measurement campaign to characterise resonator performance and describe our planned optical tests.**

I. Introduction

Recent years have seen increased interest in filter bank spectrometers for mm, sub-mm and far-infrared astronomy. The driving forces have been progress in superconducting thin-film circuit technology, allowing the fabrication of the required filter banks, and the parallel development of Kinetic Inductance Detectors (KIDs), which are near-ideal because of the ease with which large numbers of devices can be fabricated and read out[1]. In particular, the compatibility of the two technologies has made possible the Integrated Filter Bank Spectrometer (IFBS), where antenna, filter bank and detectors are all integrated on the same chip. IFBSs are predicted to be able to offer comparable resolution to grating and Fourier transform spectrometers in these wavebands, but at a smaller physical size (by exploiting the slow-wave effect or lumped element filters), wider instantaneous bandwidths and without moving parts. An imaging array realised in this manner, with moderate spectral resolution over a wide bandwidth, would be a transformative technology for survey astronomy and mapping.

Several IFBS projects, such as SuperSpec[2], DESHIMA[3] and MicroSpec[4], are targeting sub-mm and far-infrared wavelengths. The CAmbridge Emission Line Surveyor (CAMELS) is a complementary project targeting mm-wavelengths[5], and is a joint effort between the Quantum Sensors Group of the Cavendish Laboratory and the Harvard Smithsonian Astrophysical Observatory (SAO). It has two main aims: 1) to demonstrate the technologies necessary for a mm-wave IFBS and 2) to show operationally that it can be used to make science-grade observations. The latter involves addressing issues such as flux- and frequency calibration, operation in varying backgrounds and the development of optimum observing strategies. To do so, we will deploy a pathfinder instrument on the Greenland Telescope during its commissioning phase in 2016.

The pathfinder instrument will provide four spectrometer pixels, each providing 256 spectral channels with a resolution $R = \Delta\nu/\nu \approx 3000$ (a velocity resolution of ≈100 km/s). One pair will observe in the frequency range 103-109.8 GHz (L) and the other from 109.8-114.7 GHz (H). The main science target is ^{12}CO(1-0) and ^{13}CO(1-0) line emission from galaxies in redshift range 0.05-0.13 (^{12}CO) and 0.003-0.961 (^{13}CO), which will allow survey work and mapping gas distributions. The L and H bands test will allow us to test performance in very different observing regimes. The L band is away from the band edge and so background loading is low, but the emission lines are fainter as the galaxies are more distant. The emission in the H band from nearby galaxies should be brighter; however, the background loading from the O_2 emission line at the window edge (119 GHz) is much higher and subject to greater variability. Having two pixels observing in each band simultaneously will allow for sky chopping without loss of observing time, and for comparison of the systematics in notionally identical units. We are initially targeting background limited performance, which, for example, would require an NEP of order 5 x 10^{-18} W/Hz$^{0.5}$ for each detector assuming observing conditions at Thule Air Base in Greenland.

Though science drivers for an mm-wave instrument are strong, there are several technological challenges in developing KIDs for long-wavelength operation. The most significant is reduced frequency separation between the readout signal and the optical signal. This complicates the selection of a material system that functions well at both optical frequencies (high-loss required for absorption) and readout frequencies (low-loss required).

In this paper we will describe the current state of the development work for the pathfinder instrument. We will begin by giving a system level overview of the instrument. This will be followed by a detailed description of the design of each of the components, including the filter banks, optical components and resonators. Recently, we have begun measurements on a series of test devices intended to prove the key technologies. In the course of the descriptions of each component, we will present preliminary results from these devices, and describe the planned measurement campaign in detail. Finally, we will also discuss the development work being done on each part for the next generation of chips.

II. System Overview

A detailed overview of the plan for the CAMELS prototype instrument can be found in [5]. A system block diagram is shown in Fig. 1. At the basic level, an IFBS consists of an antenna to couple radiation onto a transmission line; followed by a bank of narrow bandpass filters to divide the signal into spectral channels; then a series of detectors to measure the total integrated power in each channel. Each spectrometer pixel is integrated onto a single chip. KIDs will be used for power detection. These will be a quarter-wave design, based on a length of Niobium Nitride (NbN) and SiO_2 microstrip shorted at one end and lightly capacitively coupled to a readout line at the other. Readout frequencies in the range 4-6 GHz will be used. The resonators incorporate a section of β-phase Tantalum (β-Ta), in which the signal photons are able to break Cooper pairs and generate quasiparticles, changing the resonance characteristic. The filters and optical coupling, operating at > 100 GHz, will be implemented in the same microstrip. In operation, the spectrometer chips will be cooled to 100mK in an Adiabatic Demagnetisation Refrigerator (ADR), which is currently being commissioned for device testing at the SAO.

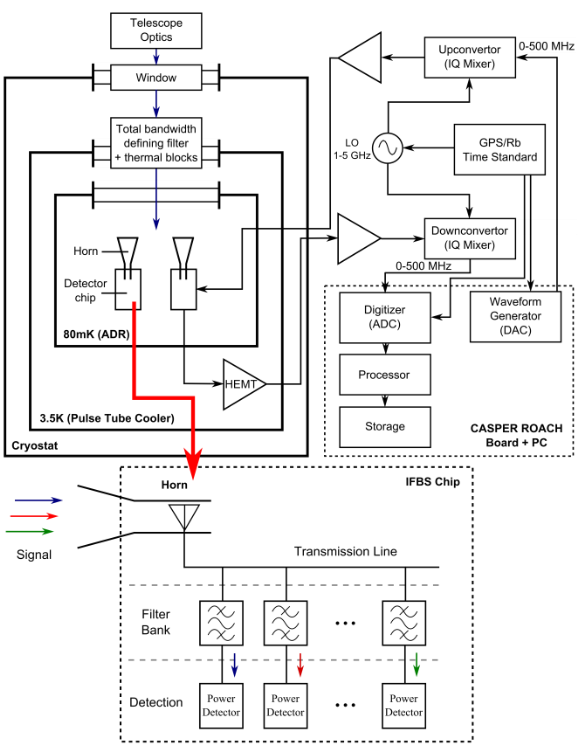

Fig. 1 System block diagram of the CAMELS instrument.

The KIDs will be readout in the canonical manner using a superposition of microwave tones transmitted along the readout line of the chip, each of which will address an individual resonator. The transmission gain and phase is then monitored to detect changes in the S-parameters of the resonators in response to illumination. The tones will be generated and processed at baseband frequency (0-500 MHz) and up- and down-converted to and from the desired readout frequency. All of this is done at room temperature, and the only cryogenic electronics required is the cabling to carry the signal to and from the array and a low-noise HEMT amplifier.

In the sections that follow we will discuss the plans for each of the components in detail and the present state of testing.

III. Optical Design

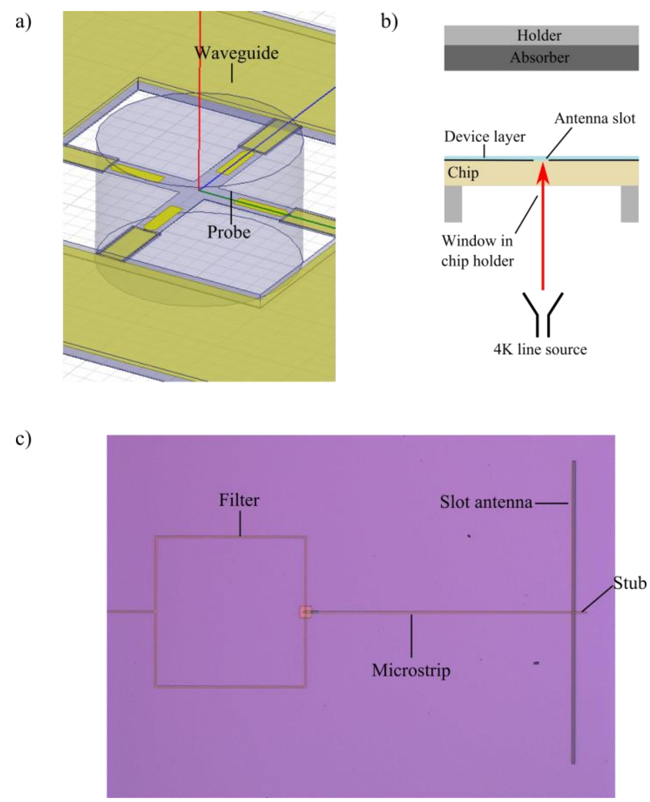

Fig. 2 Details of antennas for CAMELS chips. a) Proposed 4-probe horn coupling. b) Concept for test devices. c) Photo of realised antenna on test device.

A. Antenna

The final chips will use horn antennas for telescope coupling, so a transition is needed from circular waveguide to the IFBS chip. We are investigating a scheme using four rectangular waveguide probes suspended on a membrane, based on a design for the CLOVER [6] (Fig. 2a). This will allow polarisation-interlacing of two filter-banks, allowing for relaxed filter spacing while maintaining frequency coverage.

To avoid the membrane processing step during the early part of the test campaign, the test chips we have produced use a planar antenna coupled to microstrip. This is a centre-fed single slot design, which is illuminated from the underside of the chip through a window in the holder. Transmitted radiation is absorbed by the blackening on the holder. This arrangement is shown in Fig. 2b, and a photo of the realised antenna in Fig. 1c. The wide beam of the antenna should also simplify illumination.

B. Filter Bank

Our initial filter design uses a microstrip ring architecture coupled to the antenna and resonator via overlap capacitors. This is illustrated in Fig. 3. Test devices have been fabricated with demonstration filters designed for the range 100 – 105 GHz and with target R of > 1000. We have fabricated a series of chips with identical KIDs where a) one chip has devices directly connected to individual antennas b) the second chip incorporates filters between the resonator and each antenna and c) the third chip has the same filters, but they are fed from a single antenna. This will allow us to accurately calibrate the filter profiles.

Simulations are being performed to try and achieve the same R with a half-wave microstrip resonator. This is expected to give much simplified tuning. Similarly we are working to eliminate the overlap capacitors (in both the filters and resonators) to simplify fabrication.

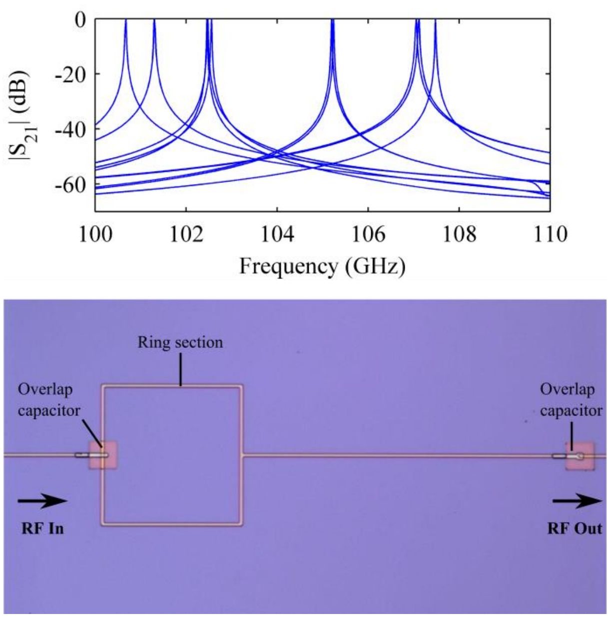

Fig. 3 Ring filter design on test chips: photo of filter on test chip and simulated filter profiles in CST, showing different tunings and R values.

C. Coupling to Resonators

A vital part of any KID is the method by which optical power is coupled into the detector. In the CAMELS devices part of the resonator is fabricated out of superconducting β-phase Ta, in which it is possible for the signal photons (103 – 115.8GHz) to break Cooper pairs and generate quasiparticles. The β-phase Ta films deposited in the Quantum Sensors Group's clean rooms have a transition temperature of 860mK, corresponding to a cut-on frequency for pair breaking of 63GHz (at 0K). The proposed architecture should therefore be able to provide sensitivity across the full W-band window.

We are testing two different ways of incorporating the sensor strip into the resonator. In the first, the end-section of the resonator microstrip is made out of β-Ta and the short is provided by a via. The microstrip line carrying the signal is then brought up over the end of the resonator, so that the β-Ta section forms its new ground plane. This is illustrated in Fig. 4a. HFSS and CST simulations of the current design predict better than -10dB return loss at the signal port across the CAMELS band and -7dB transmission to the readout port, corresponding to ≈ 70% absorption in the β-Ta. Less than -38dB loss in reflection is predicted at the readout port, with space for further optimization. In the second arrangement, shown in Fig. 4b, the β-phase Ta is used to fabricate a radial stub, which provides the resonator short. The optical signal is then either fed into the stub apex using a second line, or carried over the surface of the stub using a microstrip overlap system similar to the first coupler described. Although simulations indicate similar power absorptivity to the sensor strip design, testing is needed to establish whether the quasiparticles generated in the stub are effective at changing the resonator characteristic, or are hindered by spatial localisation due to decay.

D. Optical Tests

The filter profiles will be characterised using a cryogenic line source. This removes the need to open a window in the cryostat for initial tests, while the same system can also be used as a spectral calibrator in the final instrument. The source is being realised by using a PMP harmonic mixer on the 4K plate as a multiplier for a >12GHz signal supplied from a warm synthesizer. Initial tests have verified the operation of the mixer in transmission at 4K.

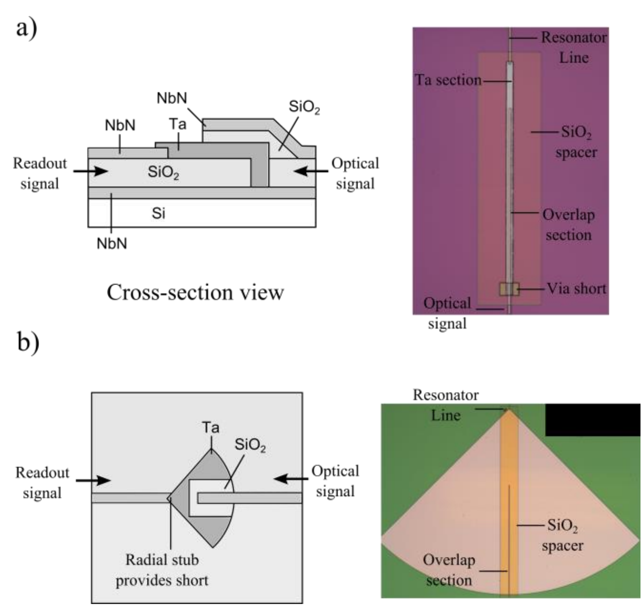

Fig. 4 Optical coupling schemes. a) Overlap design b) Radial stub design.

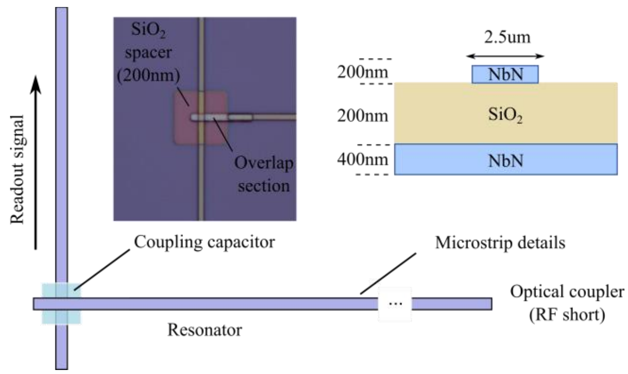

Fig. 5 Details of resonator microstrip.

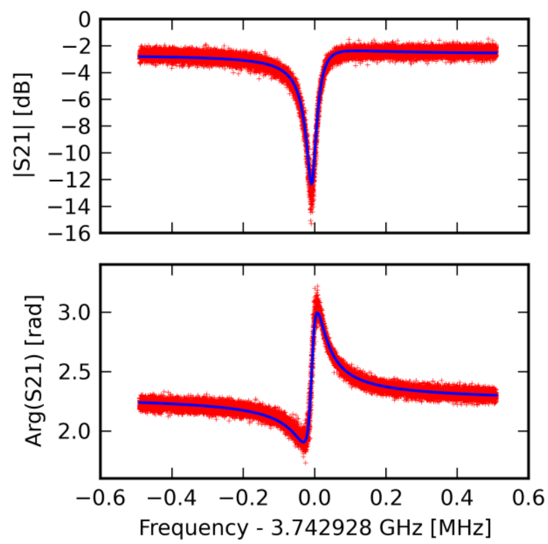

Fig. 6 Measured resonance curve for a via-shorted test resonator. Upper plot shows the transmission gain measured and the lower plot the transmission phase shift, as measured with a VNA. The fitted values for the unloaded and coupling Q-factors are 1.98×10^5 and 8.3×10^4 respectively. The readout power is estimated to be approximately -107dBm at the device. This is a preliminary measurement made without the optimised readout system, hence the relatively high noise level.

IV. Resonators

The KID resonators on the test devices use microstrip with NbN upper and lower conductors and a SiO_2 dielectric layer. The upper and lower NbN films are 200nm and 400nm thick respectively and the SiO_2 550nm thick, with a strip width of 2.5um. The NbN was deposited using reactive DC magnetron sputtering [7] and was patterned using reactive ion etching. Capacitive coupling is achieved by overlapping the end of the resonator and the readout line, with a 200nm of SiO_2 separating the conductors. This realises a small parallel plate capacitor. The overlapping section of the resonator line is patterned with lift-off. Visual inspection of the devices indicates the lithography is extremely high quality and all features have been reproduced correctly.

The test devices feature resonators shorted with both vias, for characterisation of the resonators, and with representative optical coupling structures. At the conference we will present the results of an initial campaign to parameterise the quality factors of the resonators, their power handling and the readout-frequency characteristics of the couplers. Preliminary measurements on the via-shorted resonators are promising, and a measured resonance curve is shown in Fig. 6. The total quality factor of the devices is of order 10^5, and we expect this is limited by dielectric losses.

V. Multi-Channel Readout Electronics (MCRE)

The initial MCRE will be based on a CASPER ROACH board and open source software and an ADC/DAC system, originally developed for the MUSIC project [8]. The required components for sets at CAO and Cambridge are being assembled. This is a low risk starting point. However, we intend eventually to transfer as much of the processing from the ROACH board to a GPU-based system. The hope is this will allow us to leverage the rapid increase in processing power in GPUs, and also to allow us greater flexibility in exploring readout algorithms (both in terms or coding and available power).

VI. Conclusions

We have summarised recent progress on the CAMELS project. Exploratory devices have been fabricated and are undergoing testing to verify key technologies. These will provide feedback for the next generation of devices, which are under development and will be representative of an operational spectrometer pixel.

Acknowledgment

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