Large Array of Single Photon Detecting Quantum Capacitance Detectors (QCDs) with Low Frequency Readout

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Program: FY21 R&TD **Strategic Focus Area: Long-Wavelength Detectors**

Objectives

In FY 21 we will demonstrate a 21x21 array of antenna coupled QCDs with NEP lower than $3x10^{-20}W/Hz^{1/2}$, 10^4or larger dynamic range and 80% or better yield. We will also fabricate and characterize 21x21 arrays of mesh absorber QCDs to compare NEP and dynamic range. We will develop a multiplexed readout based on the Xilinx ZCU111 radio-frequency-system on a chip (RFSoC) development board which will have higher bandwidth (2GHz) and lower power consumption (by a factor of ~80) compared with the established ROACH2 systems

Background

The Quantum Capacitance Detector (QCD –see figure 1 for concept) is the only technology to date that has demonstrated the NEP required by the Origins Survey Spectrometer (OSS) one of the instruments featured on the Origins Space Telescope (OST). It is also the only technology that has demonstrated single photon detection and counting of far-Infrared photons. Maturing this technology by demonstrating large arrays of detectors with high yield, uniformity and large dynamic range will position JPL at a significant advantage with respect to other NASA centers and other institutions in the race to field the detectors for that instrument, given no other institution

has the necessary fabrication capabilities, notably MDL's state of the art electron beam lithography system

Approach and Results

Milestone 1. Demonstration of 21x21 array of mesh absorber devices with $3x10^{-20}W/Hz^{1/2}$, 80% yield, 10^2dynamic range

We have fabricated 21x21 arrays of mesh absorber devices with readout frequencies between 2.4 and 3.4GHz. In this array we have demonstrated single photon detection and counting of 1.41Thz photons. This is illustrated in figure 2 which shows the measured rate as a function of expected photon rate (dictated by the black body temperature) over the whole array. The measurements consisted of measuring the standard deviation of the quantum capacitance over a gate sweep encompassing a single peak. A small standard deviation indicates a photon absorption event. From the measurements, we can extract efficiencies and from the efficiencies we can extract Noise Equivalent Powers (figure(2)).

Milestone 2. Demonstration of 21x21 array of antenna coupled devices with $3x10^{-20}W/Hz^{1/2}$, 80% yield, 10^4dynamic range

Antenna and Lens design were finalized as shown in Figure 3. A titanium mesh absorber between the detector and lens wafer will serve to cut down cross coupling and reduce the dark counts. The devices were fabricated and integrated to the lens array(figure4). Characterization revealed a very small quantum Capacitance signal, not usable for photo-detection. This is likely due to the small gate capacitance. We optimized the design to increase the quantum capacitance signal. Those devices are currently undergoing testing.

Milestone 3. Demonstration of advanced RFSoC readout with single photon detection algorithm

Work continued on the development of a fully multiplexed readout using the Xilinx ZCU111 evaluation board. The current version of the firmware and software being developed by a student intern is capable of generating and reading 500 tones. The total bandwidth is currently limited to 512MHz, and an Intermediate Frequency (IF) board is used to down convert the RF tones from 2-4 GHz to the 0-512MHz range. In addition, the final output data rate is currently limited to 2kHz per pixel. Since our interest is in single photon detection, an effort is underway to process the signal in the FPGA fabric before sending it to the PC via an ethernet connection. This will take form as a block to perform a standard deviation of the down-converted signal synchronized with the QCD gate sweep, mimicking the single photon measurements described above. The firmware is driven by a python interface that calls the different modules allowing for customizing the data acquisition system without knowledge of FPGA programming languages.

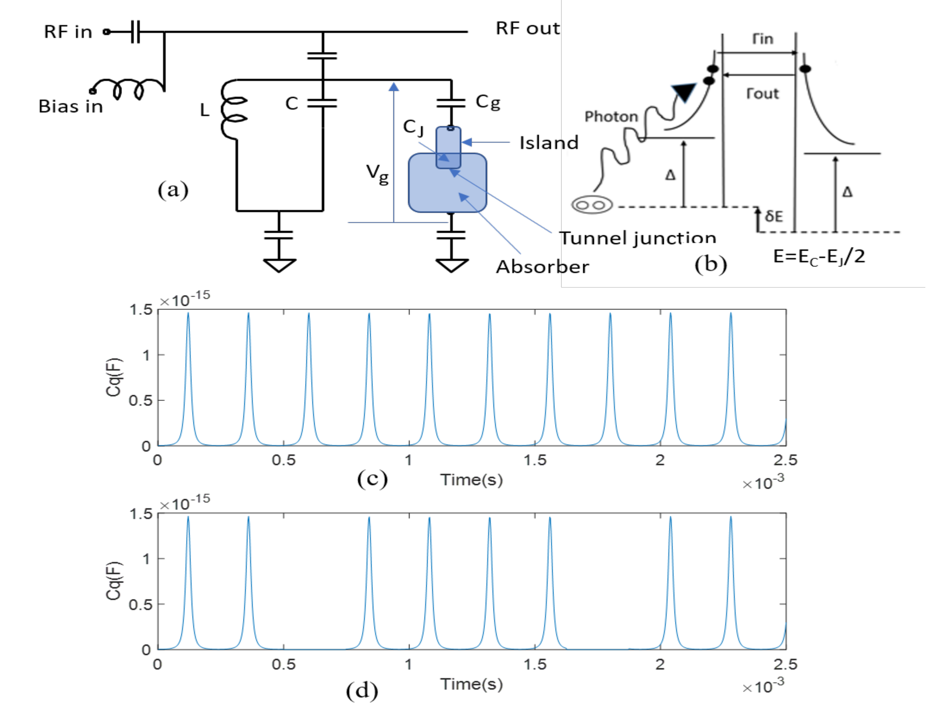

Figure. 1 (a) Quantum Capacitance Detector Concept. An island of superconducting material is connected to an absorber via a small tunnel junction and biased by a gate capacitor with a linear voltage ramp in a sawtooth format. (c) The capacitance of the island displays a periodic stream of peaks. The device is embedded in a resonator, and the capacitance change is detected by the change in resonance frequency. **(b)** A photon absorbed breaks a Cooper-pair causing quasiparticles to tunnel onto the island with a rate Γ_{in} proportional to the quasiparticle density. Quasiparticles tunnel out of the island with a rate Γ_{out} independent of the quasiparticle density. (d) A Photon striking the absorber breaks Cooper pairs creating a population of quasiparticles which tunnel onto the island, destroying a peak.

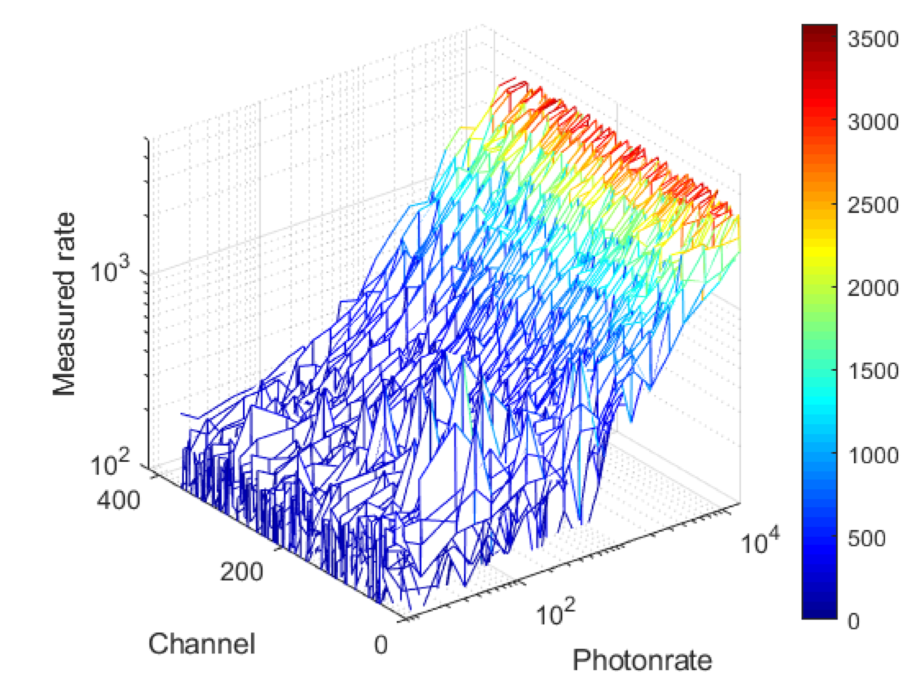

Figure 2. Measured photon rate as a function of expected photon arrival rate for the 21x21 array of quantum capacitance detectors

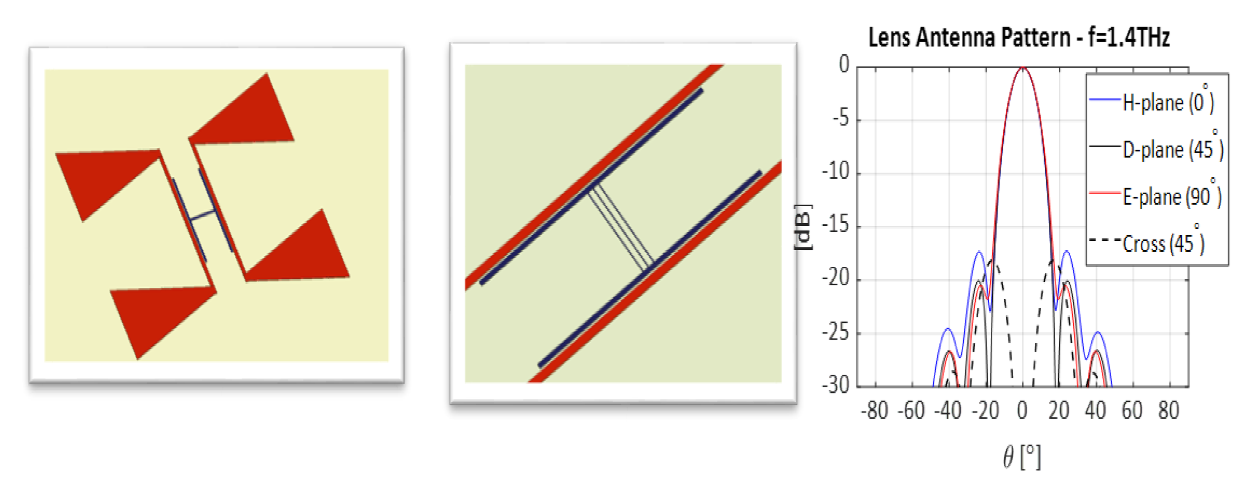

Figure 3. Left: QCD antenna layout. Center: Detail of absorber at the center of antenna. Right: combined lens-antenna pattern.

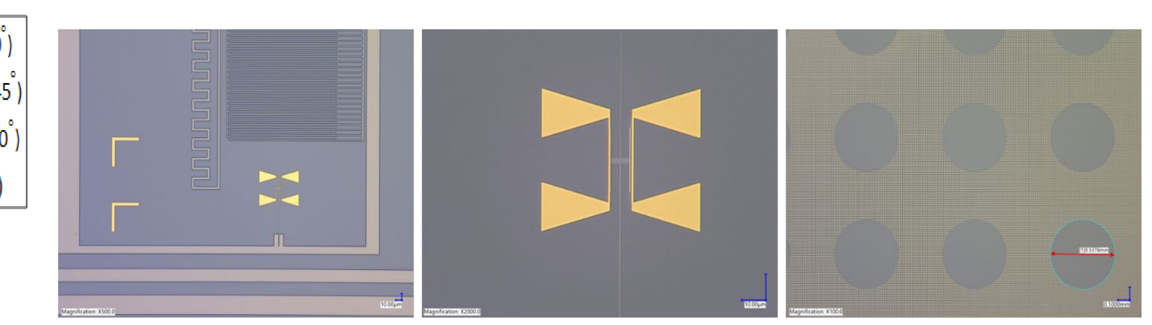

Figure 4. Left: portion of a pixel showing the resonator and antenna. Center: antenna detail..Right: Titanium grid.

Significance/Benefits to JPL and NASA

The results reported here mean that JPL has the leading technology to field the focal plane of the Origins Survey Spectrometer, and instrument on the proposed Origins Space Telescope. Not only the QCDs have demonstrated the required noise equivalent powers and single photon detection and counting, but did so in a large array format suitable for frequency multiplexing. No other technology has demonstrated to date the required NEPs.

Publications

1. P.M. Echternach, A.D. Beyer, and C.M. Bradford, "Large array of low-frequency readout quantum capacitance detectors", J. Astron. Telesc. Instrum. Syst. 71(1) 011003-1

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