BABAR-ERI: Black Array of Broadband Absolute Radiometers – Earth Radiation Imager

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***Abstract*—BABAR-ERI is being developed for a CubeSat capable of imaging the Earth's outgoing longwave radiation with a 1 km ground sample distance (GSD) using a push-broom imager. The detector is a silicon micromachined 32-pixel linear array of electrical substitution radiometers capable of broadband sensing from 0.3 µm to 100 µm using vertically aligned carbon nanotube absorbers located on each pixel. Our aim is to demonstrate data performance, with a CubeSat, against existing CERES instruments but at a smaller GSD. Electrical substitution radiometers are well suited to this task as they have heritage as ground calibration transfer standards and in space for total solar irradiance measurements.**

I. Introduction

DATA continuity for the Earth Radiation Budget Climate Data Record (ERB CDR) is currently maintained by six satellite instruments which are part of the Clouds and the Earth's Radiant Energy System (CERES) project. Each instrument consists of a three-channel scanning radiometer to monitor shortwave (0.2 µm – 5 µm), thermal (8 µm – 12 µm), and total (> 0.2 µm) radiation emitted by the Earth with a ground sample distance of 10 – 20 km (depending on which CERES instrument). Updating and even continuing CERES poses a challenge as new or different instruments may not agree with CERES measurements. Introduction of new instruments will only be acceptable to the scientific community for the ERB CDR until proven alongside CERES. As a result, a parallel measurement of the Earth's radiance from top of atmosphere is required with low cost and risk. CubeSats fit the low cost/risk model having been readily adopted for technology demonstrations of new hardware in space. However, while CubeSats are ideally suited for simple working demonstrations of unproven or new technology, their low size, weight, and power (SWaP) requirements make it difficult to compete with data produced from conventional satellites instruments. Yet, two recent CubeSats, the Compact Spectral Irradiance Monitor (CSIM) [1] and the Compact Total Irradiance Monitor (CTIM) [2] have not only demonstrated new detector technology, but also their possible use in continuing the 40-year-old record of solar irradiance measurements from space currently maintained by TSIS-1 on the International Space Station. BABAR-ERI builds upon the relatively short but proven heritage of the CSIM and CTIM CubeSats. Both CSIM/CTIM instruments demonstrated that traditional active cavity radiometers used on TSIS-1 could be replaced with silicon micromachined electrical substitution radiometers (ESRs) with vertically aligned carbon nanotube absorbers (VACNTs) *on a CubeSat*. A similar measurement by the BABAR-ERI CubeSat coincident with CERES is required to demonstrate that a new detector can meet the accuracy and stability requirements of the CDR and possibly exceed them.

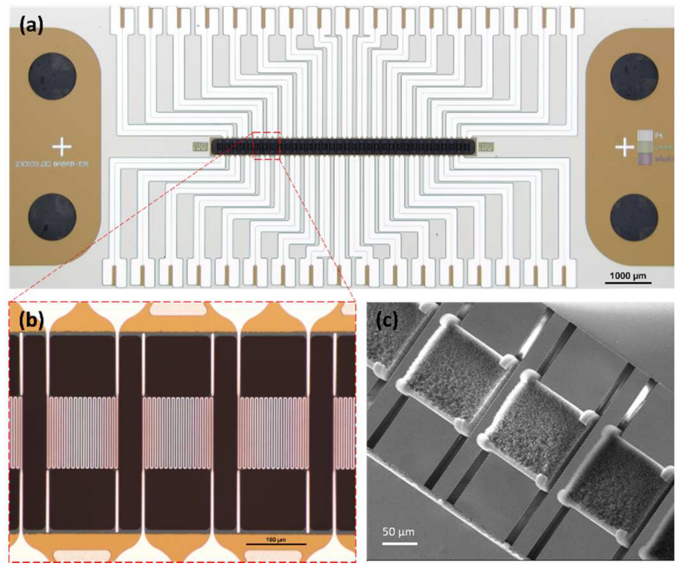

Fig. 1. (a) Detector chip for one of the two channels on the BABAR-ERI CubeSat. The central (dark rectangle) region is where the 32-pixel linear array is located. (b) Optical image of the backside of the pixels in the microbolometer array showing the Pt thermistors/heaters. (c) Scanning electron microscope image of the frontside of the pixels showing vertically aligned carbon nanotubes (≈20 µm tall) on each pixel.

II. Results

BABAR-ERI utilizes a MEMS array of ESRs much in the same style as the CSIM/CTIM radiometers but with monolithic integration of all components [3]. Each pixel is a 0.5 µm thick silicon nitride island (124 µm x 124 µm) supported by four legs (0.5 µm x 8 µm x 100 µm). On the backside (non-illuminated) of each pixel, is a Pt wire with cross section of 0.2 µm x 2 µm and approximately 1 kΩ in resistance. The frontside (illuminated) of each pixel is a VACNT absorber approximately 20 µm high. The two-wire Pt meander acts as both a thermistor (temperature coefficient of resistance = 0.36 %/°C) and heater for electrical substitution operation. Platinum has been chosen for its known long-term stability in thermometry. Each pixel is placed within its own Wheatstone bridge and resistively self-heated by a pulse width modulation signal (PWM). Changes in optical power incident on the pixel are measured directly by monitoring the change in power applied by the PWM signal to keep the bridge in balance. Actively controlling the power balance of each pixel using replacement power heating allows us to achieve a closed-loop time constant of < 10 ms (25 ms natural time constant). Optical power is coupled to each pixel through selective area growth of VACNTs on the frontside of each pixel (fig. 1c). VACNTs allow for broadband, far infrared absorption out to 100 µm. Measurements have confirmed that the reflectance of VACNTs is < 1 % from 0.3 µm to 100 µm.

Power noise density measurements of a pixel are shown in fig. 2. A replacement power of 88 μW (corresponding to a 45 °C pixel temperature rise) results in a noise floor of approximately 40 pW/√Hz. Operating the pixels at high replacement powers (> 10 μW) allows for a larger dynamic range as well as a lower noise floor.

The BABAR-ERI CubeSat is a 12U bus with two co-registered telescopes to measure the total (0.3 μm to 100 μm) and shortwave (0.3 μm to 4 μm) radiation. Longwave radiation will be determined by taking the difference of the two measured channels. Each detector channel will perform push-broom imaging of a 32-km wide swath with a 1 km footprint. A long-life chopping wheel (≈ 7 Hz) placed in front of both channels will allow for differential mode operation of the ESRs.

A unique aspect of BABAR-ERI is that it directly measures power incident, thereby eliminating the need for on-board radiometric calibration sources. Currently, active cavity radiometers are used in conjunction with on-board irradiance sources to calibrate detectors (e.g., bolometers). With the miniaturization of active cavity radiometers into a MEMS radiometer array, the Earth's radiance can be imaged directly.

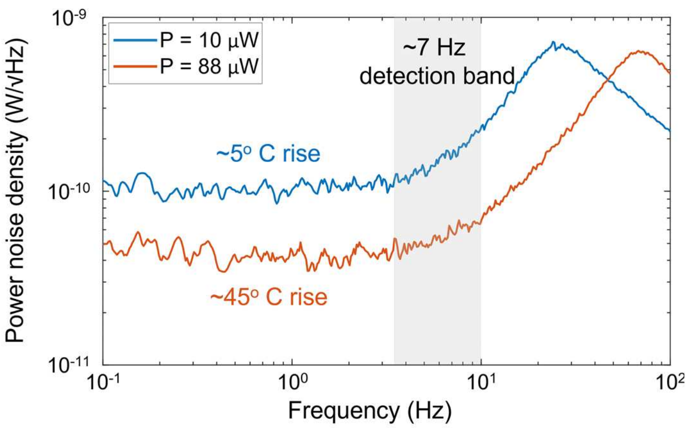

Fig. 2. Measured pixel performance for two different replacement powers. The blue line is for a replacement power of 10 μW (corresponding to a 5 °C temperature rise) with a noise floor of ≈ 100 pW/√Hz. The orange line is for a replacement power of 88 μW (corresponding to a 45 °C temperature rise) with a noise floor of ≈ 40 pW/√Hz.

III. Summary

The goal of BABAR-ERI is to demonstrate higher resolution (1 km footprint), non-mechanized, push-broom imaging of the Earth's outgoing radiation without on-board radiometric calibration. Flight detectors have been built and meet the required sensitivity of < 1 W/m^2/sr. Full instrument build and testing to demonstrate a technology readiness level of 6 (TRL 6) is projected before the end of 2023.

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