Multimode bolometer development for the Primordial Inflation Explorer (PIXIE) instrument

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Introduction and instrument description
The Primordial Inflation Explorer (PIXIE) [1, 2]

- Space-based polarizing Fourier transform spectrometer (FTS).
- Designed to measure the polarization and intensity spectra of the CMB.
- Multimode “lightbucket” design enables nK-scale sensitivity across 2.5 decades in frequency with just 4 thermistor-based bolometers.
- Like other FTSs [3, 4, 5, 6], PIXIE’s design and experimental approach\(^a\) represent a significant departure from imagers often used for CMB measurements. *This is especially true for the detectors.*
  - Large etendue ($A\Omega = 4 \text{ cm}^2 \text{ sr}$).
  - Handle large optical load (120 pW).
  - Large and mechanically robust absorber structure (30x larger than the spider web bolometers on Planck [7]).
  - Limited sensitivity to particle hits.
  - Sensitive to all optical frequencies of interest (15 GHz - 5 THz).
  - Photon-noise limited ($\text{NEP} \leq 1 \times 10^{-16} \text{ W/}\sqrt{\text{Hz}}$).

\(^a\)See Al Kogut’s poster on systematic error mitigation and Dale Fixsen’s talk on beams.
Each focal plane has two polarization-sensitive bolometers mounted back-to-back with their polarization axes orthogonal.

\[ \vec{E}_{\text{inc}} = A\hat{x} + B\hat{y} \]  

Measured power:

\[ P^L_x = \frac{1}{2} \int (A^2 + B^2) + (A^2 - B^2) \cos \left( \frac{4\nu z}{c} \right) d\nu. \]
\[ P^L_y = \frac{1}{2} \int (A^2 + B^2) + (B^2 - A^2) \cos \left( \frac{4\nu z}{c} \right) d\nu. \]
\[ P^R_x = \frac{1}{2} \int (A^2 + B^2) + (A^2 - B^2) \cos \left( \frac{4\nu z}{c} \right) d\nu. \]
\[ P^R_y = \frac{1}{2} \int (A^2 + B^2) + (B^2 - A^2) \cos \left( \frac{4\nu z}{c} \right) d\nu. \]

Inverse Fourier transform:

\[ S^L_x(\nu) = A^2_{\nu} - B^2_{\nu}. \]
\[ S^L_y(\nu) = B^2_{\nu} - A^2_{\nu}. \]
\[ S^R_x(\nu) = A^2_{\nu} - B^2_{\nu}. \]
\[ S^R_y(\nu) = B^2_{\nu} - A^2_{\nu}. \]

**Signal** = small modulated component in a bright (∼ 120 pW) background.
• Mirror position $z \rightarrow$ optical path difference $\ell$: $z \sim \ell/4$.
• Mirror velocity $v$: $v = z / (3 \text{ sec}) = 1.73 \text{ mm/sec}$.
• Optical path difference $\ell \rightarrow$ interfering radio frequency $\nu$: $\ell = c/\nu$.
• Radio frequency $\nu \rightarrow$ Audio (FTS) frequency $\omega$: $\omega = 4\nu v / c$.
• CMB: $\omega \lesssim 15 \text{ Hz}$.
• Dust: $\omega \lesssim 100 \text{ Hz}$.

These constraints drive the bolometer bias and bandwidth requirements. *Detectors must be photon noise limited across all FTS frequencies (0 – 100 Hz) under large, near-constant ($\sim 120 \text{ pW}$) optical bias.*
Detector design and fabrication
Detectors are fabricated using standard microfabrication techniques. They consist of three main components:

- Absorber structure - absorb single linear polarization
- Endbanks - measure incident optical power with silicon thermistors
- Frame - thermal sink and interface to readout

Each beam’s focal plane will consist of two indium bump-hybridized detectors mounted $< 20 \, \mu\text{m}$ apart with their absorbers orthogonal. → measure orthogonal polarizations of nearly the same electric field.
Absorber structure - overview

- Consists of a grid of suspended, micromachined, ion implanted silicon wires.
- Wires are degenerately doped to be metallic at all temperatures.
- Effective sheet resistance of the whole structure is $377 \, \Omega/\square$.
- Absorber area sets low frequency cutoff of instrument (15 GHz); grid spacing (30 $\mu$m) sets high frequency cutoff (5 THz).
- Wire widths and thicknesses are highly uniform across the array.
  - Thickness set by starting SOI device layer thickness (1.35 $\mu$m).
  - Wires are etched to width with an ICP RIE process.
Doping induces compressive stress in absorber wires; previous devices had their wires buckle and protrude up to 20 µm from the frame. → problematic for a hybridized pair of bolometers.

Detectors subject to vibrations and acoustic excitations at launch. → need resonant frequencies of absorber structure to be much greater than excitation frequencies of launch.

Solution: deposit highly tensile Al$_2$O$_3$ film on absorbers outside of active optical region. → Fabricated absorbers are flat and expected to oscillate with amplitudes of < 0.4 µm rms during launch.
Endbanks - overview

- Consists of a gold bar for thermalization and two doped silicon thermistors on a crystalline silicon membrane.
- The gold bar also sets the heat capacity of the endbank.
- Endbank is formed from the device layer of the SOI substrate.
- Endbanks are connected to the chip frame through eight silicon legs.
- Thermistors are doped to operate below metal-insulator transition.
  Electron transport mechanism is variable range hopping [8]:

\[ R(T) = R_0 \times \exp \sqrt{\frac{T_0}{T}} \]  

(4)

where \( R_0 \) and \( T_0 \) are constants largely determined by geometry and doping, respectively.
• The chip frame is designed so that any two bolometer chips can be hybridized together.
• Large gold-covered areas serve as heat sinks.
Package and readout
Package and readout - dark tests

- Thermistor operates under current bias ($R_{bias} \gg R_{therm}$).
- Bolometer is connected to a cryogenic (130 K) JFET amplifier with tensioned leads, mitigating capacitive microphonic contamination of the signal band. We use Interfet NJ14AL16 JFETs that are screened for low noise performance (5.5 nV/$\sqrt{\text{Hz}}$ at 100 Hz).
- Amplifier converts the high source impedance of the thermistors (M$\Omega$-scale) to the low output impedance of the JFETs (1.8 k$\Omega$).
- Low impedance signal is AC coupled to a room temperature amplifier.
Detector performance
- Determine $R_0$ and $T_0$ from the measured resistances under low electrical bias.
  $\rightarrow T_0 = 15.11$ K and $R_0 = 911$ $\Omega$. Operating resistance: 5.42 M$\Omega$.
- Determine average thermal conductance $\bar{G}$ between the thermistors and the bath from the high-bias end of the load curves:
  \[ \bar{G} = \frac{P_{\text{bias}}}{T_1 - T_2}. \]  
- Fit to the measured $\bar{G}$ with a function $\tilde{G} = G_0 \times T^\beta$.
  $\rightarrow$ The fit is close to the expected value ($\beta_{\text{phonon}} = 3$).
For the endbank geometry, break Au bar, thermistors, and legs into small elements.

- Solve for the etendue $A\Omega_{ij,ik}$ between all elements.

- Heat flow between elements (e.g., between i and j) is given by $P_{ij} = A_{ij} (T_i^\nu - T_j^\nu)$.

- Determine $G$ between elements, determine $C$ from material properties/geometries, measure VRH parameters $R_0$ and $T_0$, and solve for non-equilibrium bolometer noise [9]:

$$\text{NEP}_{\text{bolometer}}^2 = \gamma_1 4k_b T^2 G + \frac{1}{S^2} \left( \gamma_2 4k_b T R + e_n^2 + \gamma_3 i_n^2 R + \gamma_4 \text{NEP}_{\text{excess}}^2 \right).$$

(6)
• Thermal model reproduces the measured $\bar{G}$ well.
• Modeled noise fits the measured noise well for multiple bias conditions.
• Running the model for the optical and electrical bias conditions expected during flight, we calculate a bolometer NEP of $7.93 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$.

Expect to be photon noise limited across the entire PIXIE bandwidth.
Conclusions
Conclusions

- We designed, fabricated, and characterized large area polarization-sensitive bolometers for the PIXIE experiment.
- Mechanical characterization of the fabricated PIXIE bolometers shows that the tensioning scheme successfully flattens the absorber strings.
  - Enables indium bump hybridization of a pair of bolometer chips.
  - Mitigates microphonic sensitivity during launch.
- The dark data provide significant insight into the thermal behavior of the endbanks.
  - Thermal model agrees well with the data.
  - The results indicate that the PIXIE bolometers satisfy the sensitivity and bandwidth requirements of the space mission.
- Upcoming work:
  - Characterize the absorber structure (dark measurements of thermal transport and AC impedance, optical measurements with a cryogenic blackbody source.)
  - Subject a hybridized pair of bolometers to environmental testing.
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