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

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Outline

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2. Detector design and fabrication
3. Package and readout
4. Detector performance
5. Conclusions

Introduction and instrument description

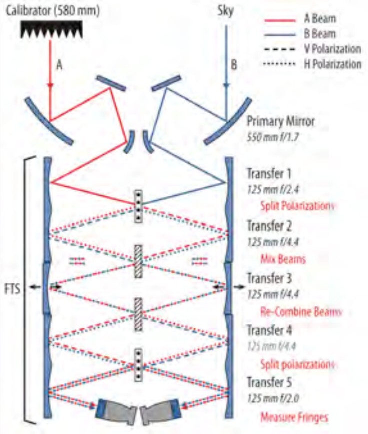
Introduction

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 ($A\Omega = 4$ cm^2 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 (NEP $\leq 1 \times 10^{-16}$ $\mathrm{W}/\sqrt{\mathrm{Hz}}$).

[a] See Al Kogut's poster on systematic error mitigation and Dale Fixsen's talk on beams.

Instrument description



Each focal plane has two polarization-sensitive bolometers mounted back-to-back with their polarization axes orthogonal.

Incident radiation:

$$\vec{E}_{inc} = A\hat{x} + B\hat{y} \quad (1)$$

Measured power:

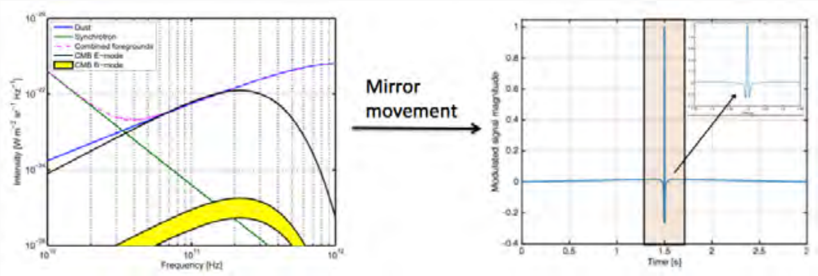
$$\begin{aligned}
\mathbf{P}_x^L &= \frac{1}{2}\int (A^2+B^2) + (A^2-B^2)\cos\left(\frac{4\nu z}{c}\right)d\nu. \\
\mathbf{P}_y^L &= \frac{1}{2}\int (A^2+B^2) + (B^2-A^2)\cos\left(\frac{4\nu z}{c}\right)d\nu. \\
\mathbf{P}_x^R &= \frac{1}{2}\int (A^2+B^2) + (A^2-B^2)\cos\left(\frac{4\nu z}{c}\right)d\nu. \\
\mathbf{P}_y^R &= \frac{1}{2}\int (A^2+B^2) + (B^2-A^2)\cos\left(\frac{4\nu z}{c}\right)d\nu.
\end{aligned} \quad (2)$$

Inverse Fourier transform:

$$\begin{aligned}
\mathbf{S}_x^L(\nu) &= A_\nu^2 - B_\nu^2. \\
\mathbf{S}_y^L(\nu) &= B_\nu^2 - A_\nu^2. \\
\mathbf{S}_x^R(\nu) &= A_\nu^2 - B_\nu^2. \\
\mathbf{S}_y^R(\nu) &= B_\nu^2 - A_\nu^2.
\end{aligned} \quad (3)$$

Signal = small modulated component in a bright ($\sim 120\,\mathrm{pW}$) *background.*

Instrument description

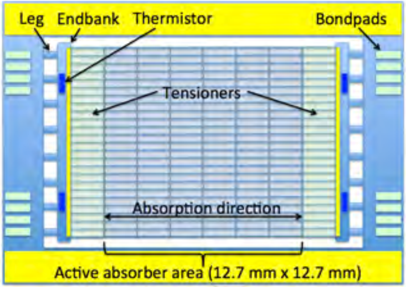


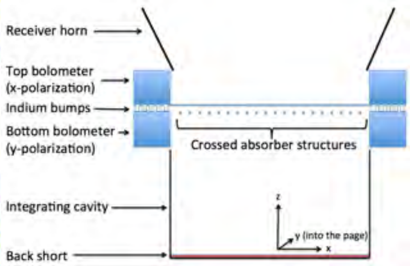
- Mirror position z $\rightarrow$ optical path difference ℓ: $z \simeq \ell/4$.
- Mirror velocity v: $v = z/\left(3\,\mathrm{sec}\right) = 1.73\,\mathrm{mm/sec}$.
- Optical path difference ℓ $\rightarrow$ interfering radio frequency ν: $\ell = c/\nu$.
- Radio frequency ν $\rightarrow$ Audio (FTS) frequency ω: $\omega = 4\nu v/c$.
- CMB: $\omega \lesssim 15$ Hz.
- Dust: $\omega \lesssim 100$ Hz.

These constraints drive the bolometer bias and bandwidth requirements. *Detectors must be photon noise limited across all FTS frequencies* $(0 - 100\,\mathrm{Hz})$ *under large, near-constant* $(\sim 120\,\mathrm{pW})$ *optical bias.*

Detector design and fabrication

Detector design - overview



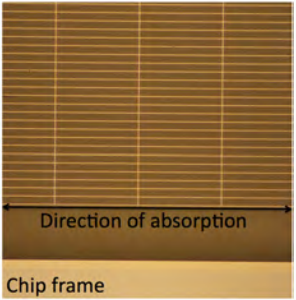


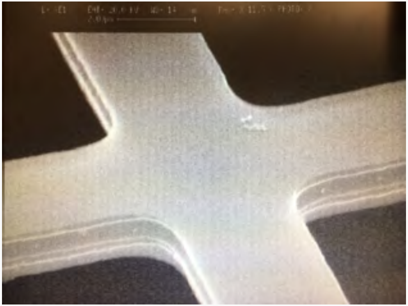
Detectors are fabricated using standard microfabrication techniques. They consist of three main components:

- 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 $< 20\ \mu$m apart with their absorbers orthogonal.
$\rightarrow$ measure orthogonal polarizations of nearly the same electric field.

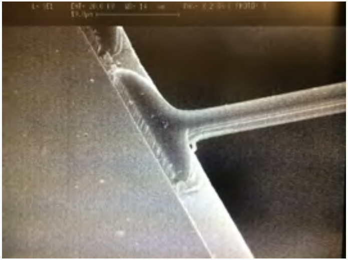
Absorber structure - overview

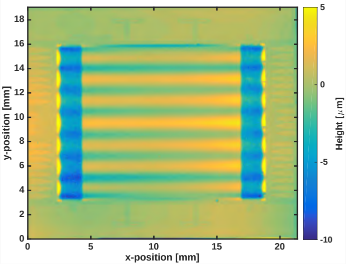




- Consists of a grid of suspended, micromachined, ion implanted silicon wires.
- Wires are degenerately doped to be metallic at all temperatures.
- Effective sheet resistance of the whole structure is 377 $\Omega/\Box$.
- Absorber area sets low frequency cutoff of instrument (15 GHz); grid spacing (30 μm) 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 μm).
  - Wires are etched to width with an ICP RIE process.

Absorber structure - mechanical characterization





- Doping induces compressive stress in absorber wires; previous devices had their wires buckle and protrude up to 20 μm from the frame.
  $\rightarrow$ problematic for a hybridized pair of bolometers.
- Detectors subject to vibrations and acoustic excitations at launch.
  $\rightarrow$ need resonant frequencies of absorber structure to be much greater than excitation frequencies of launch.
- Solution: deposit highly tensile $\mathrm{Al_2O_3}$ film on absorbers outside of active optical region.
  $\rightarrow$ Fabricated absorbers are flat and expected to oscillate with amplitudes of $< 0.4\ \mu$m 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]:

$$R(T) = R_0 \times \exp\sqrt{\frac{T_0}{T}}, \qquad (4)$$

where R_0 and T_0 are constants largely determined by geometry and doping, respectively.

Frame

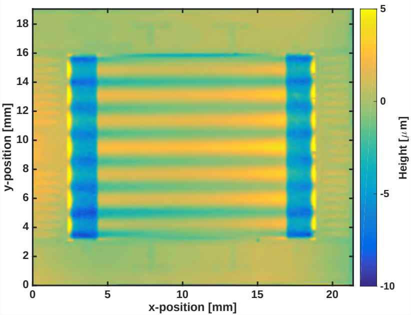
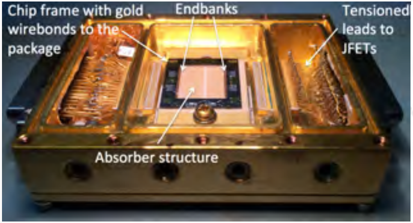


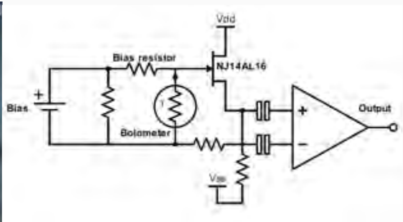
Figure 1: replace this with In bump SEM

- 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

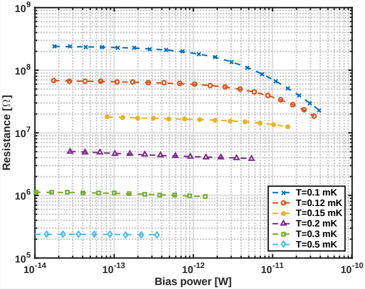


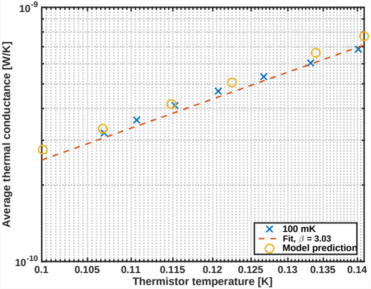


- Thermistor operates under current bias ($R_{bias} >> R_{therm}$).
- Bolometer is connected to a cryogenic (130 K) JFET amplifier with tensioned leads, mitigating capacitive microphonic contamination of the signal band. We use Interfet NJ14AL16 JFETs that are screened for low noise performance (5.5 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 100 Hz).
- Amplifier converts the high source impedance of the thermistors (MΩ-scale) to the low output impedance of the JFETs (1.8 kΩ).
- Low impedance signal is AC coupled to a room temperature amplifier.

Detector performance

Performance - load curves



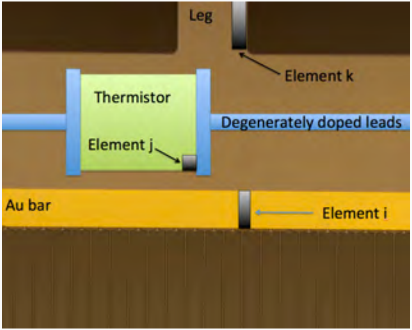


- Determine R_0 and T_0 from the measured resistances under low electrical bias.
  $\rightarrow$ $T_0 = 15.11$ K and $R_0 = 911\ \Omega$. Operating resistance: 5.42 MΩ.
- Determine average thermal conductance $\bar{G}$ between the thermistors and the bath from the high-bias end of the load curves:

$$\bar{G} = \frac{P_{\text{bias}}}{T_1 - T_2}. \tag{5}$$

- 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 ($\beta_{phonon} = 3$).

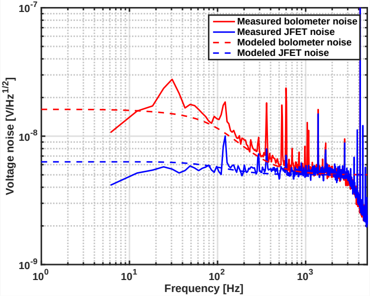
Performance - thermal model

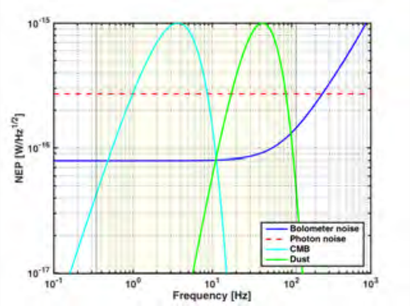


- For the endbank geometry, break Au bar, thermistors, and legs into small elements.
- Solve for the etendue $A\Omega_{ij,ik}$ beween all elements.
- Heat flow between elements (e.g., between i and j) is given by $P_{ij} = A_{ij}\left(T_i^{\nu} - T_j^{\nu}\right)$.
- Determine G between elements, determine C from material properties/geometries, measure VRH parameters R_0 and T_0, and solve for non-equilibrium bolometer noise [9]:

$$\mathrm{NEP_{bolometer}}^2 = \gamma_1 4 k_b T^2 G + \frac{1}{S^2}\left(\gamma_2 4 k_b T R + e_n^2 + \gamma_3 i_n^2 R + \gamma_4 \mathrm{NEP_{excess}}^2\right). \tag{6}$$

Performance - noise





- 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 $7.93 \times 10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$.

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 agress 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.

Acknowledgements

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Backup

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