Pixellated Planar Bolometer Imaging Arrays

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Summary

• Pixellated imaging arrays – Motivation
• Practical realizations and parameters
• Design considerations and limitations
• How to make thing black – Materials, topologies and modeling absorbers
• Tracking the imaging properties – inter-element correlations and resolution

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Continuum Science Drivers: Extended Source Mapping

- Star Formation Regions
  - Accretion / Debris Disks
  - Cold Protostellar Gas
  - Dust Emission
- Planetary, Kuiper Belt, and Comets
- Universe at High Red Shift
  - Continuum Surveys / Polarimetry
  - Cosmology
    - Galaxy Clustering
    - SZ / Cosmic Microwave Background
  - Photometric Survey Support

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Single-Mode Detector: Matched to Point Source

\[ P = S \, A \]

Single-Mode Detector: Distributed Source

\[ P = k_b T \]

Multimode Array: Distributed Source

\[ P_n \approx m \, k_b T \]

Large Area Detector: Distributed Source

\[ P = \frac{2k_b T}{\lambda^2} \int A \cdot d\Omega \]

Total Propagating Modes:

\[ N \sim \frac{1}{2} \left( \frac{2\pi a}{\lambda} \right)^2 \propto \frac{A \Omega}{\lambda^2} \]

In principle, a well implemented multimode array is able to more rapidly map an extended image while maintaining low noise, high intrinsic detector speed, angular resolution, and control over atmospheric noise…

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Telescope Primary:
- Low Pass Spatial Filter

Re-imaging Optics:
- Beam Waveguide to Detector
- Filtering to Define Spectral Response
- Cold Baffling to Limit Sensor FOV

Cryostat and Supporting Electronics:
- Appropriate Environment for Sensor
- Cold Stage ~200 mK, ~10 μW load

Pixellated Array in Focal Plane:
- Image from Multiple Sensors Elements
- Temporal ResponseDefined by Sensor Electro-Thermal Time Constant

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Pixellated Array: Implementations

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## Selected Array Parameters:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>p/λ</th>
<th>Array Size / Detector Type</th>
<th>Back Termination</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT</td>
<td>0.50</td>
<td>32 x 32 TES</td>
<td>Absorber</td>
<td>2.0mm 1.3mm 1.1mm</td>
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<tr>
<td></td>
<td>0.75</td>
<td></td>
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<tr>
<td></td>
<td>0.88</td>
<td></td>
<td></td>
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<tr>
<td>GISMO</td>
<td>1.00</td>
<td>8 x 16 TES</td>
<td>Short</td>
<td>2.0mm</td>
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<tr>
<td>GBT</td>
<td>1.00</td>
<td>8 x 8 TES</td>
<td>Short</td>
<td>3.0mm</td>
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<tr>
<td>SCUBA 2</td>
<td>2.52</td>
<td>64 x 64 / TES 32 x 32 / TES</td>
<td>Short</td>
<td>0.45mm 0.85mm</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SHARC II</td>
<td>2.86</td>
<td>12 x 32 Semiconductor</td>
<td>Short</td>
<td>0.35mm 0.45mm 0.85mm</td>
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<tr>
<td></td>
<td>2.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAWC</td>
<td>3.3-to-20</td>
<td>12 x 32 Semiconductor</td>
<td>Absorber</td>
<td>0.05-to-0.3mm</td>
</tr>
</tbody>
</table>

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Pixellated Arrays: Practical Limits

• Electromagnetic Considerations:
  – Lagrange / Helmholtz Invariant: \( A_{\text{eff}} \Omega_b / \lambda^2 = N_{\text{modes}} \)
  – Uncertainty Principle: \( \Delta x \Delta k > \frac{1}{2} \)
    • Rayleigh Resolution – Pixel Angular Acceptance
    • Diffraction – Instrumental Polarization and Coupling Efficiency
    • Hanbury-Brown-Twiss – Inherent Image Correlations
  – Coupling: Convert incident fields from plane-wave to sensor mode set with high absorption efficiency without loss of spatial information…

• Information Theoretic Considerations:
  – Nyquist: Telescope is Spatial/Temporal Low-Pass Filter
  – Shannon: \( S = \det[\log(1+G_{ij}N^{-1}G_{ij})] \) – need to understand and characterize correlations

Objective: Maximize information extraction from image by sensor…

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Senor Array: Design Considerations

• Relatively Fast Optics…
  – Absorption Efficiency: Polarization Dependent on Incidence Angle…
  – Mutual Coupling: Degraded Noise / Angular Resolution…
  – Reflections: Ghosting in Optics…
  – Band Pass: Function of radiation incident angle and collimation…
    (e.g., $\Delta v_{\text{eff}} \sim v_o / 2 (2 n_{\text{eff}} f/l)^2$ …)

• Inter-Element Correlations a Function of Detector Pitch, Absorber Geometry, and Wavelength…

• Fabrication…
  – Control / Limit Interlayer Spacing and Geometry → Polarization
    • Multimode or Appropriately Symmetrized Absorber Design
  – Mechanical Backshort Spacing / Geometry → Coupling
  – Bolometric Absorber Process and Validation → Device Stability

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Pixellated Array Element:

- Lossy coating converts incident photons to phonon in absorber membrane…
- Thermal sensor will have finite area with a surface impedance differing from that of the absorber, electrically long leads for electrical read out and bias…
- Other Influences:
  - Gaps for Thermal Conductance
  - Minimal Heat Capacity…
  - Calibration/Bias Heater
  - Finite Array Size / Edge Effects
  - etc…

The effects of these design parameters on the absorptance can be studied for plane wave illumination via 3D electromagnet simulation for each polarization (e.g., Time-Domain TLM or Finite Element methods) by imposing periodic boundary conditions…

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Absorber: Design Considerations

- Compatibility with other sensor processing...
- Predictable performance based upon DC and Optical Witnesses
- Decouple Optical and Thermal Design Constraints
  - Use Electrically Thin Silicon Substrate...
  - Terminate Transmitted Power Cold and Limit FOV...
  - Maximize Sensor Absorption Efficiency
- Circuit Topology and Sensitivity: FSS, Back Termination, etc...

<table>
<thead>
<tr>
<th>Coating Composition:</th>
<th>Bi</th>
<th>Cr/Au</th>
<th>Pd/Au</th>
<th>Ti/Au</th>
<th>Silicon Implant Degenerate Semiconductor</th>
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</thead>
<tbody>
<tr>
<td>Conduction Mechanism:</td>
<td>Semi-Metal</td>
<td>Disordered Metal Alloy</td>
<td>Disordered Metal Alloy</td>
<td>Disordered Metal Alloy</td>
<td>Degenerate Semiconductor</td>
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<tr>
<td>Surface Reactance?</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Electrical Time Constant?</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Heat Capacity?</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Long Term Stability?</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

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Absorber: Finite Scattering Time

HAWC TiAu_Si Witness: @ 300K

Drude TLM: \( T_a=5K \), \( \epsilon_r=11.5 \), \( t\sim82\text{um} \), \( R_{sq}\sim110\Omega/\text{sq} \), \( \tau\sim0\text{fs} \)

\[
\varepsilon_r(\omega) \approx \varepsilon_r^{Si} + i\sigma(\omega)/\varepsilon_0\omega \\
= \varepsilon_r^{Si} + i\omega_p^2\tau/\omega(1-i\omega\tau)
\]

Physical and Lumped Element Model for Absorber with a finite relaxation timescale…

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Frequency Independent Absorber: Thin Film Resistor Metallization

- To approximate ideal resistor, desire ohmic thin film with thickness << penetration depth over band of interest...

- Semi-metal, disorder alloy, and degenerately doped implant can produced the desired impedance levels at long wavelengths...

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Absorbers: FSS and PSS Elements

- Theoretical Investigation of Frequency and Polarization Sensitivity Surface Configurations...
  - Geometry
  - Absorption/Emission Efficiency
  - Bandwidth
  - Substrate Dielectric Loading
  - Inter-pixel Correlation when Elements are used as Focal Plane Array Detector Absorbers
  - Tolerance / Sensitivity Study
  - Polarization Purity
- Derivation and Finite Element Validation of Computational Efficient Lumped Circuit Element Models...

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For low $p/\lambda$ gaps between elements can not be ignored – the structure is a capacitive mesh lowpass filter with ohmic loss...

Infinite Square Loop Array and Equivalent Circuit Representation...

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Pixel Coupling: Beam Overlap

\[ \eta_o \approx \frac{\lambda}{4} \]

\[ d_{pixel} \approx \frac{\lambda}{2} \]

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Pixel Coupling: Beam Overlap

Equivalently, treat array elements as quasioptical power splitter and consider at beam overlap at infinity…

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Consider impedance matrix for array of elements. Terminate all elements in array terminated except pair – currents on one pixel couple to other…

\[ Z_m \approx \frac{2R_{rad} l^2}{r_j \lambda_o} \sin \vartheta_i \sin \vartheta_j \exp \left( -j2\pi r_{ij} / \lambda_o \right) \]

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Multimode Optical Response:

Bolometer is modeled by an aperture mask. Pupil stop limits the number of modes processed by the optical system. Alternatively, $L_p$ can be thought of as a spatial filter that limits transverse wave vectors to $<kL_p/2F$.

An image of the array is formed at surface C. The diffraction effects are handled by propagating the second-order statistical correlations of the radiation in the $k$-domain.

Blackbody source determines the number of modes that are initially considered in the problem.

Withington et al. 2003
**Polarization Response…**

**Observation:** If detectors response is different for orthogonal polarizations, uncertainty introduced in calibration / measurement of photometric flux. Effect is estimated to be several percent level at millimeter wavelengths...

**Solution:** 1) Ensure that the polarized response of the detector is negligible, 2) Keep track of the polarization, 3) Other…

<table>
<thead>
<tr>
<th>Solution</th>
<th>Loss</th>
<th>Reflections</th>
<th>Bandwidth</th>
<th>Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetrize absorber (1-side)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Diagonal mesh (2-sides)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>- -</td>
</tr>
<tr>
<td>Single polarization only</td>
<td>- -</td>
<td>- -</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Absorb wave after absorber</td>
<td>- -</td>
<td>- -</td>
<td>+</td>
<td>- -</td>
</tr>
<tr>
<td>Polarizer in front of array</td>
<td>- -</td>
<td>- -</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Rotating QWP</td>
<td>-</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Rotating HWP</td>
<td>-</td>
<td>-</td>
<td>- -</td>
<td>+</td>
</tr>
<tr>
<td>Variable Delay Modulator</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

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SHARC II:
857 GHz (350 microns)
384 elements 1mm pixels
Inter-Pixel Correlation ~4%
Nyquist Sampled
CSO: 10.4 m primary
8.3” FWHM

Wollack et al., 2006 – Future GBT Instrumentation Workshop