Pixellated Planar Bolometer Imaging Arrays

E. Wollack, D. Chuss, H. Moseley

NASA/GSFC

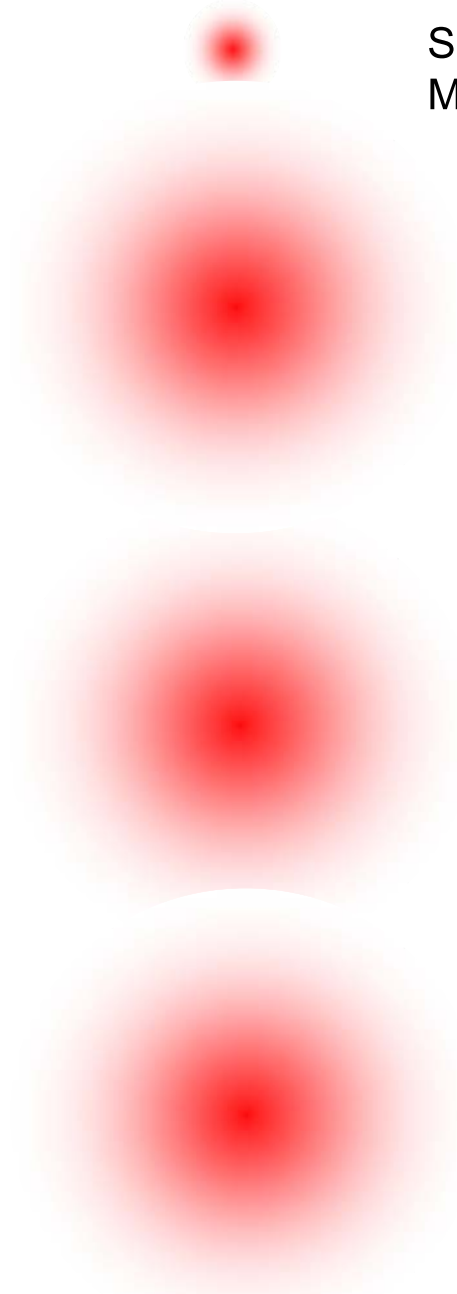
Future Telescope Instrumentation Workshop, Green Bank, West Virginia – 09/05/06

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

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 / Polarimetery
  - Cosmology
    - Galaxy Clustering
    - SZ / Cosmic Microwave Background
  - Photometric Survey Support



Single-Mode Detector:
Matched to Point Source

$$P = S\,A$$

ıgle-Mode Detector:
stributed Source

$$P = k_b T$$

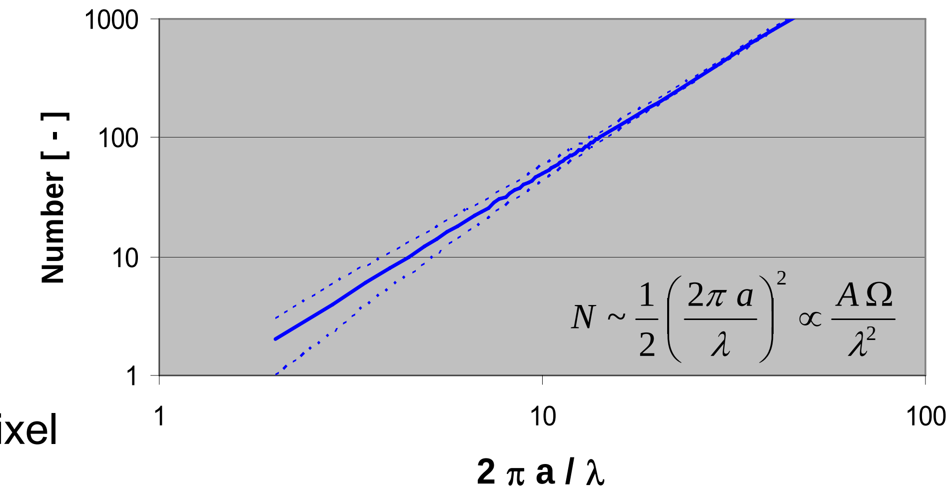
ıltimode Array:
ɜtributed Source
detectors, m-modes/pixel

$$P_n \approx m\,k_b T$$

ırge Area Detector:
stributed Source

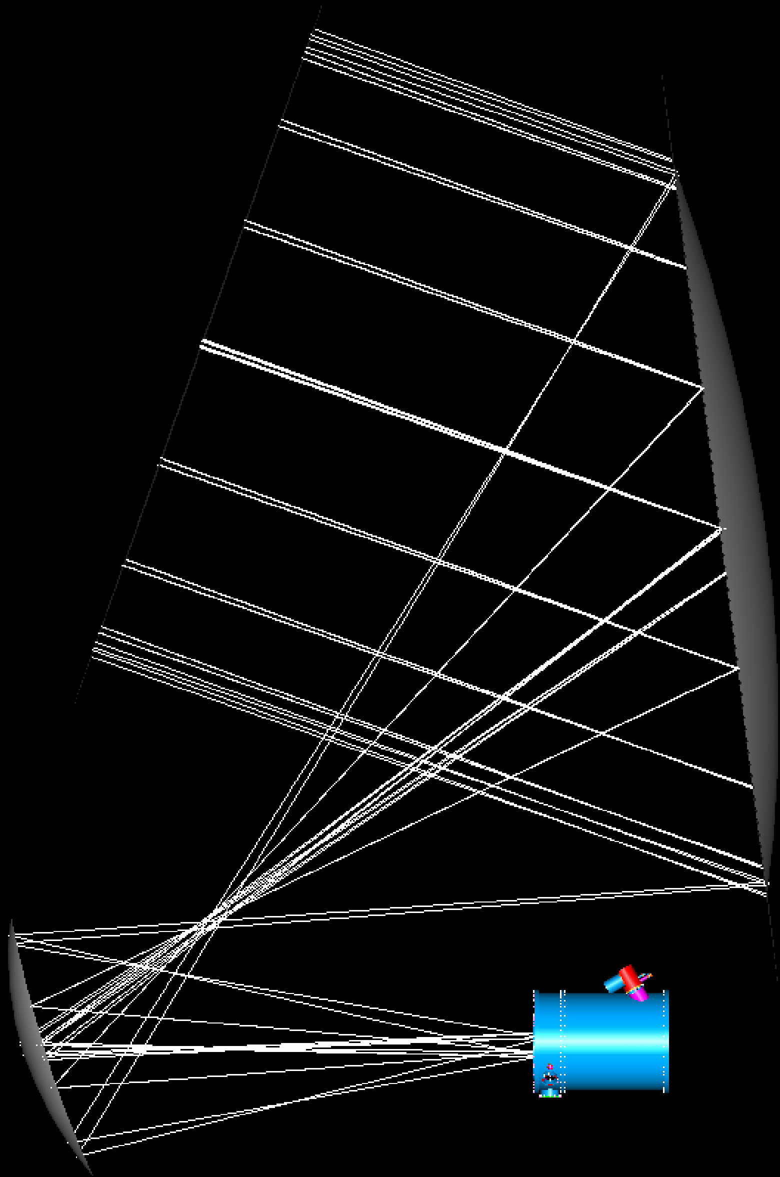
$$P = \frac{2k_b T}{\lambda^2}\int A\cdot d\Omega$$

Total Propagating Modes:



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…

Wollack et al., 2006 – Future GBT Instrumentation Workshop

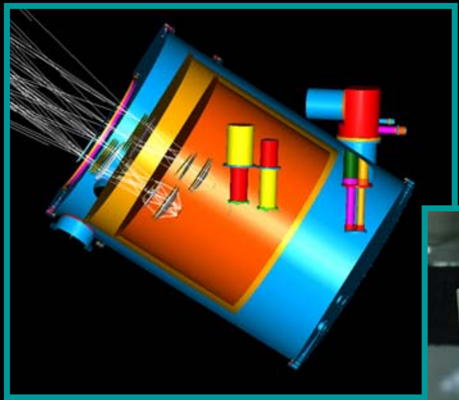


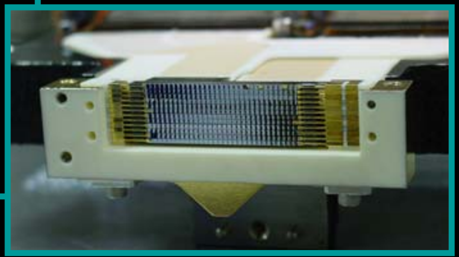
Telescope Primary:
- Low Pass Spatial Filter

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

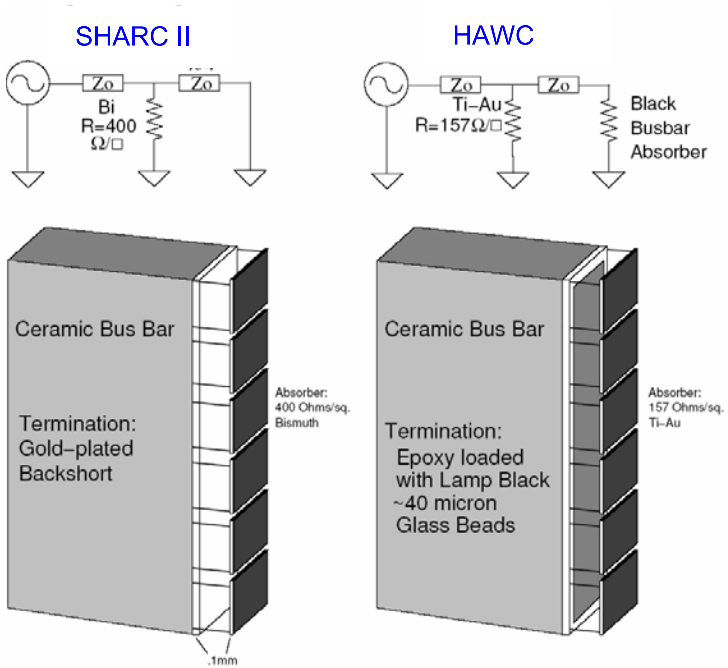
Pixellated Array in Focal Plane:
- Image from Multiple Sensors Elements
- Temporal Response Defined by Sensor Electro-Thermal Time Constant

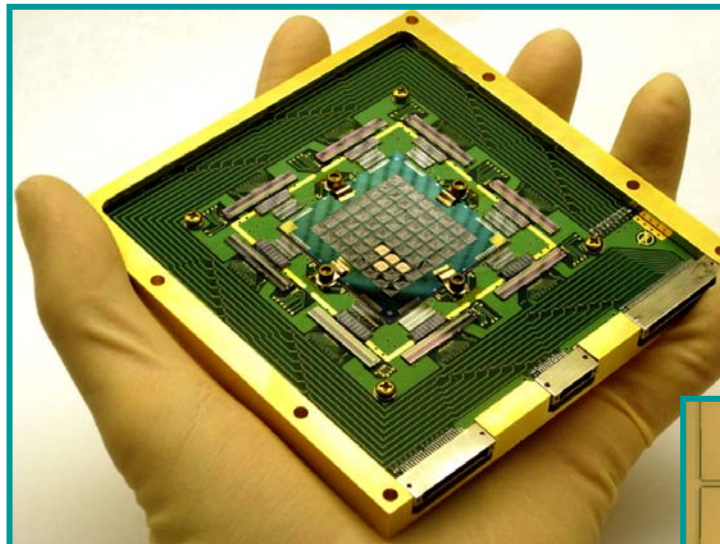




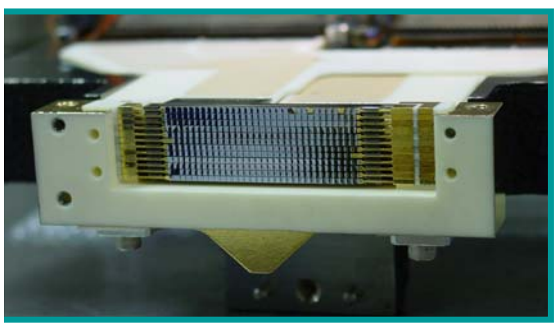
Wollack et al., 2006 – Future GBT Instrumentation Workshop

Pixellated Array: Implementations

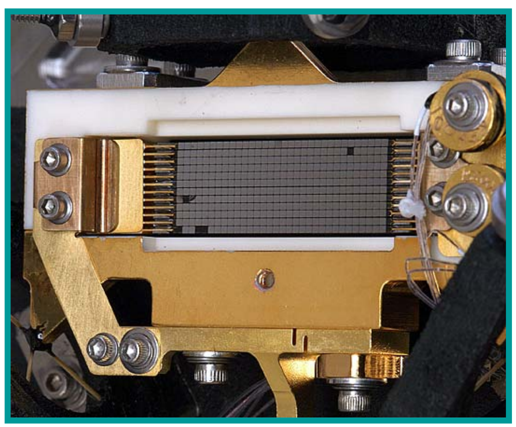


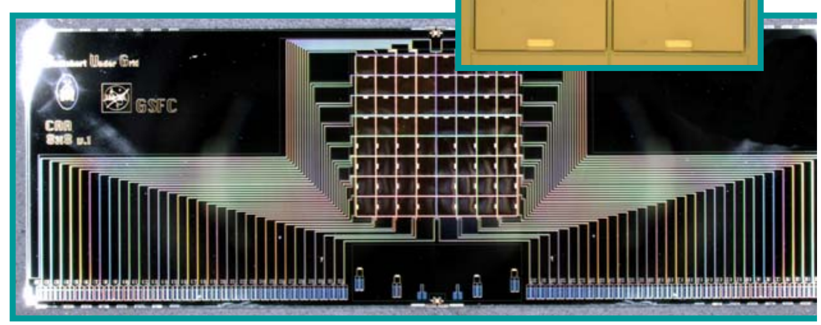


GBT



Micro-machined
Silicon “Pop-Up”





Back-Terminated
Grid Array

GISMO

Wollack et al., 2006 – Future GBT Instrumentation Workshop

Selected Array Parameters:

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

Wollack et al., 2006 – Future GBT Instrumentation Workshop

Pixellated Arrays: Practical Limits

- Electromagnetic Considerations:
  - Lagrange / Helmholtz Invariant: $A_{eff}\,\Omega_b\,/\,\lambda^2 = N_{modes}$
  - Uncertainty Principle: $\Delta x\,\Delta k > ½$
    - 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 senor…*

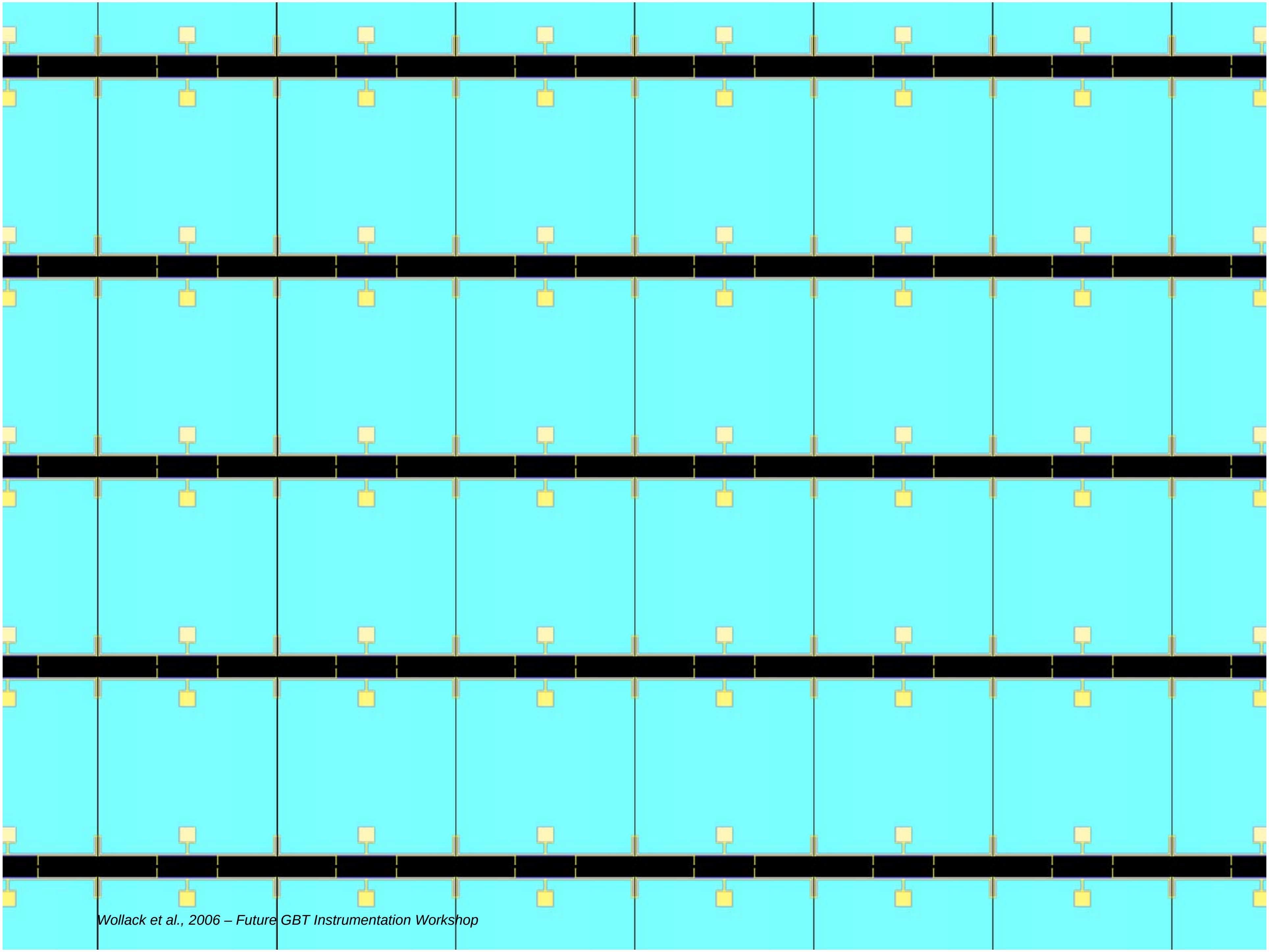
Wollack et al., 2006 – Future GBT Instrumentation Workshop

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., $\Delta\nu_{eff} \sim \nu_o / 2 (2\, n_{eff}\, f/)^2 \ldots$)

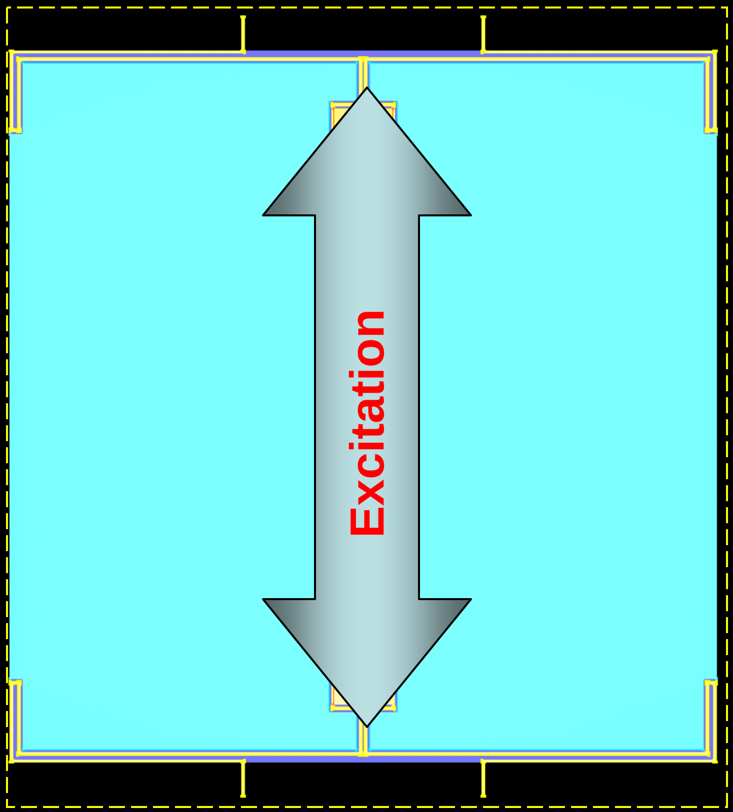
- Inter-Element Correlations a Function of Detector Pitch, Absorber Geometry, and Wavelength…

- 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



Wollack et al., 2006 – Future GBT Instrumentation Workshop

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…

Absorber: Design Considerations

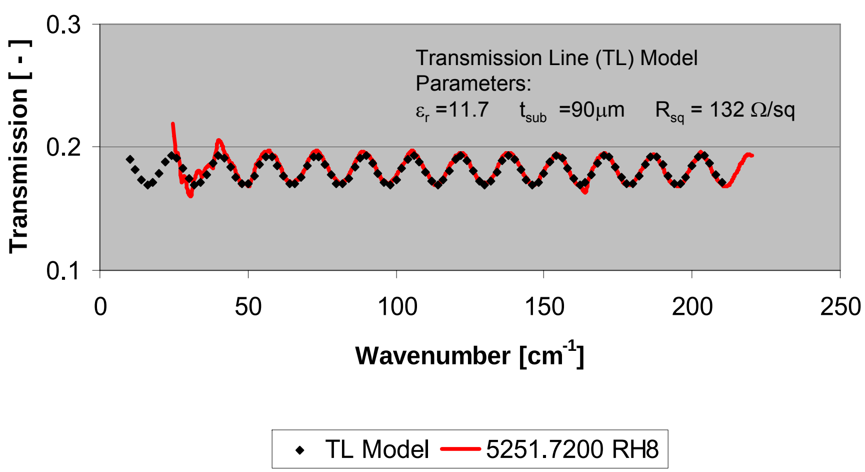
- Compatibility with other sensor processing…
- Predictable performance based upon DC and Optical Witnesses
- Decouple Optical and Thermal Design Constraints
  - Use Electrically Thin Silicon Substrate…
  - Terminate Transmitted Power Cold and Limit FOV…
  - Maximize Sensor Absorption Efficiency
- Circuit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

Coating Composition: Conduction Mechanism:	Bi Semi-Metal	Cr/Au Disordered Metal Alloy	Pd/Au Disordered Metal Alloy	Ti/Au Disordered Metal Alloy	Silicon Implant Degenerate Semiconductor
Surface Reactance?	--	++	++	++	++
Electrical Time Constant?	-	++	++	++	+
Heat Capacity?	++	+ (magnetic)	-- (large elec. γ)	++	++
Long Term Stability?	+	-	+	+	++

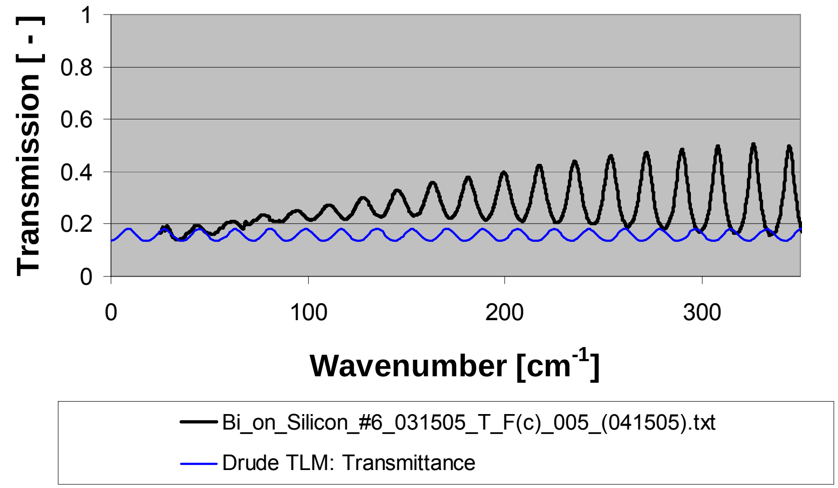
Wollack et al., 2006 – Future GBT Instrumentation Workshop

Absorber: Finite Scattering Time

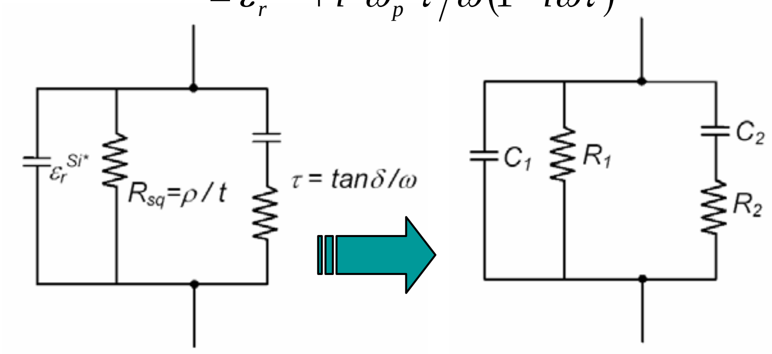
HAWC TiAu_Si Witness: @ 300K



Drude TLM: T_a=5K e_r=11.5, t~82um R_{sq}~110Ω/sq tau~0fs

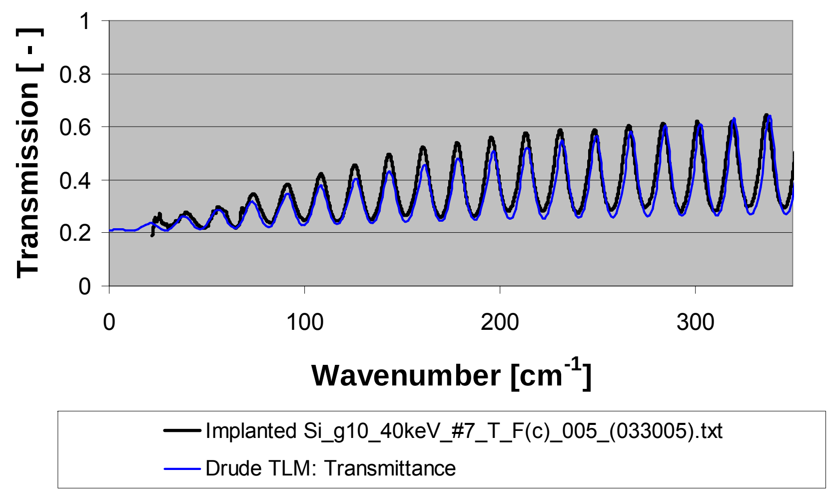


$$\varepsilon_r(\omega) \cong \varepsilon_r^{Si*} + i\sigma(\omega)/\varepsilon_o\omega$$
$$= \varepsilon_r^{Si*} + i\cdot\omega_p^{\ 2}\tau/\omega(1-i\omega\tau)$$



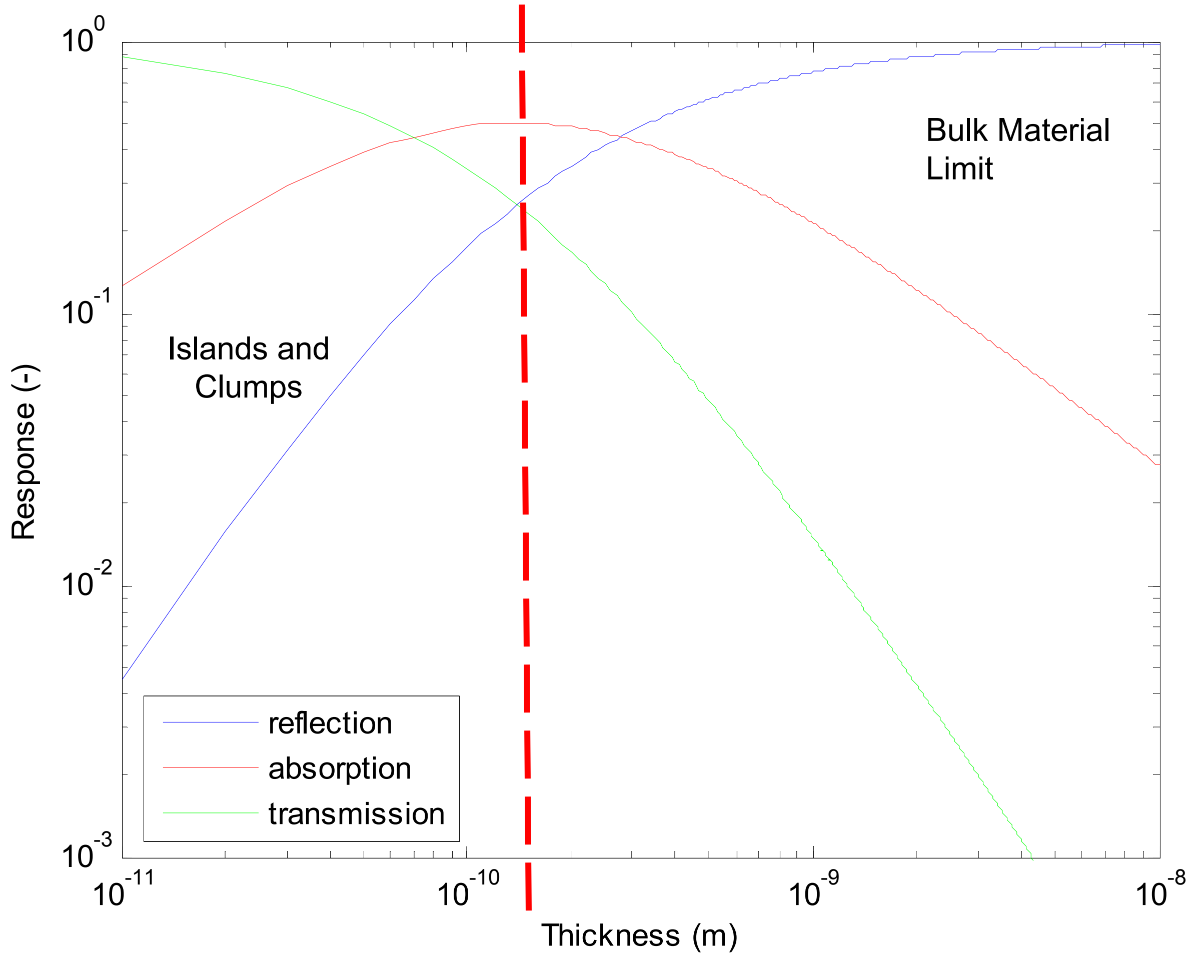
Physical and Lumped Element Model for Absorber with a finite relaxation timescale…

Drude TLM: Ta=5K er=11.5, t~83um Rsq~160Ω/sq tau~38fs p=1 Ef~34meV



Wollack et al., 2006 – Future GBT Instrumentation Workshop

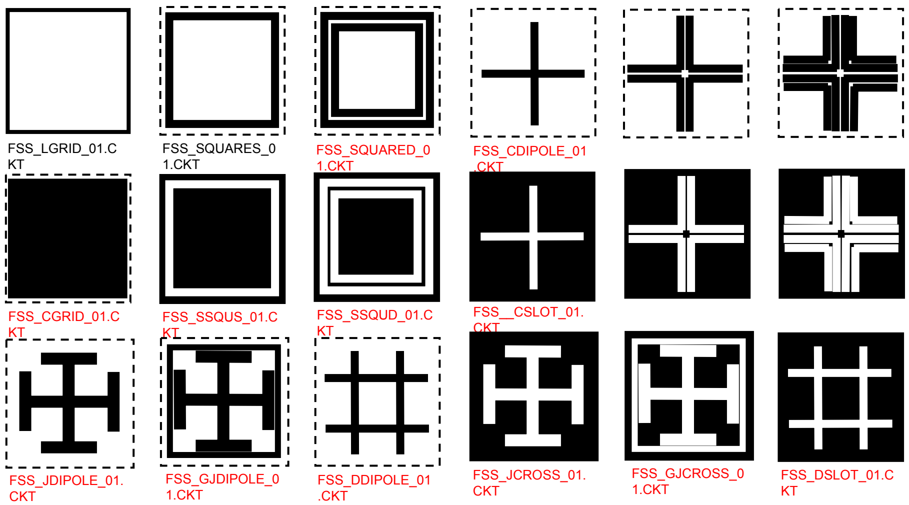
Frequency Independent Absorber: Thin Film Resistor Metallization

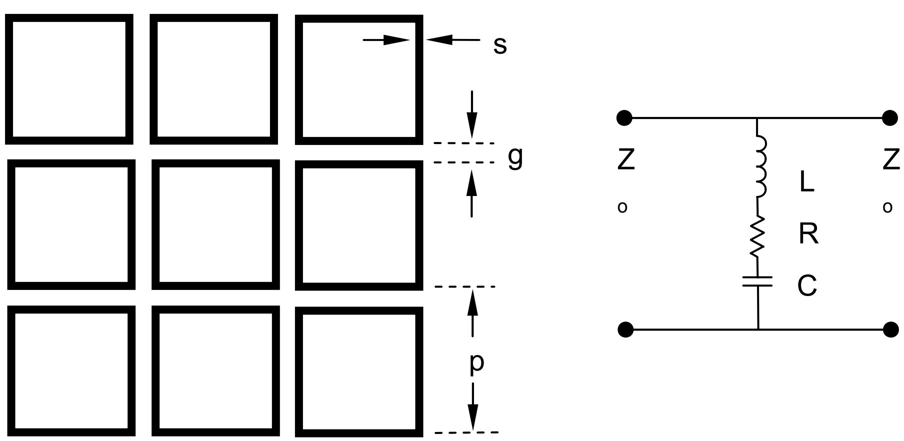


- To approximate ideal resistor, desire ohmic thin film with thickness << penetration depth over band of interest…
- Semi-metal, disorder alloy, and degenerately doped implant can produced the desired impedance levels at long wavelengths…

Wollack et al., 2006 – Future GBT Instrumentation Workshop

Absorbers: FSS and PSS Elements

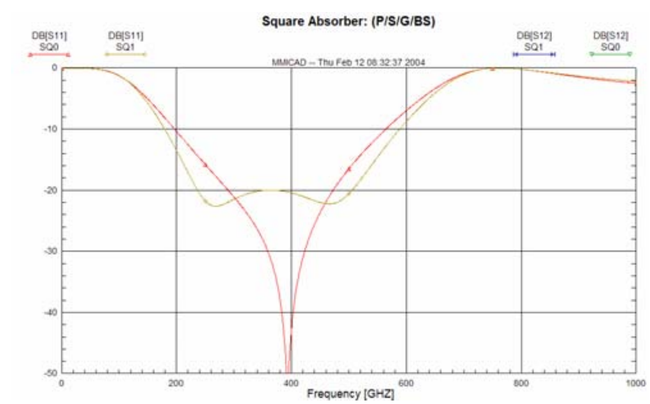




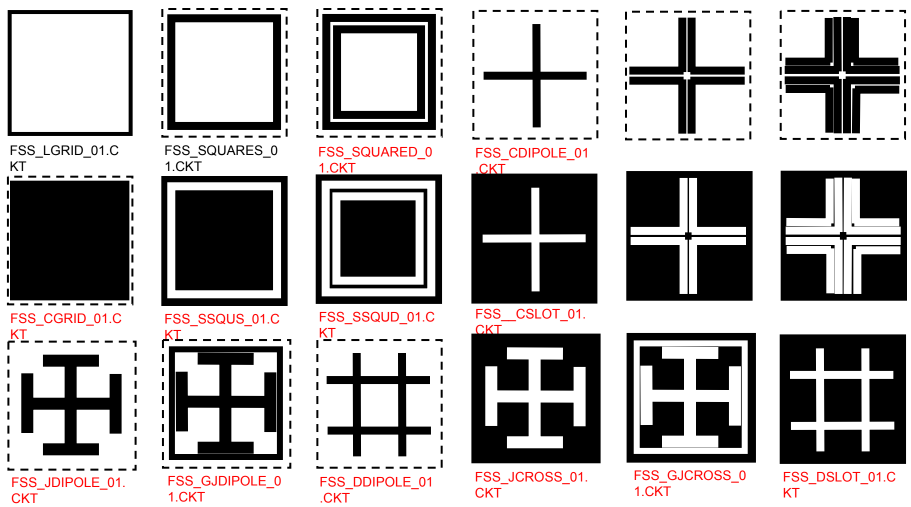
Infinite Square Loop Array and Equivalent Circuit Representation…

Wollack et al., 2006 – Future GBT Instrumentation Workshop

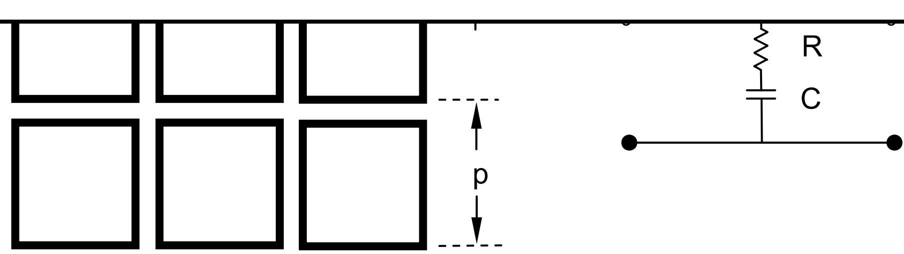
- Theoretical Investigation of Frequency and Polarization Sensitivity Surface Configurations…
  - Geometry
    - Absorption/Emission Efficiency
    - Bandwidth
    - Substrate Dielectric Loading
    - Inter-pixel Correlation when Elements are used as Focal Plane Array Detector Absorbers
  - Tolerance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



Absorbers: FSS and PSS Elements



For low p/λ gaps between elements can not be ignored – the structure is a capacitive mesh lowpass filter with ohmic loss…

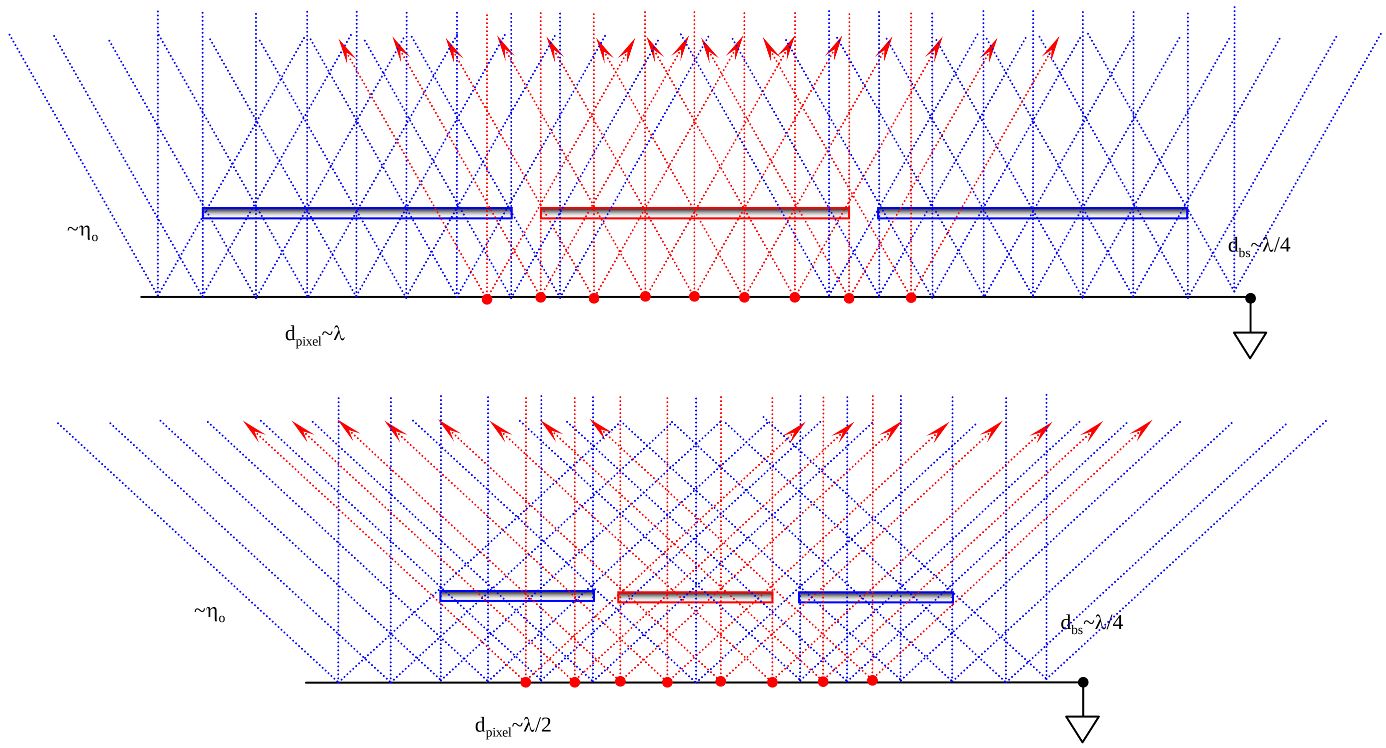


Infinite Square Loop Array and Equivalent Circuit Representation…

- 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…

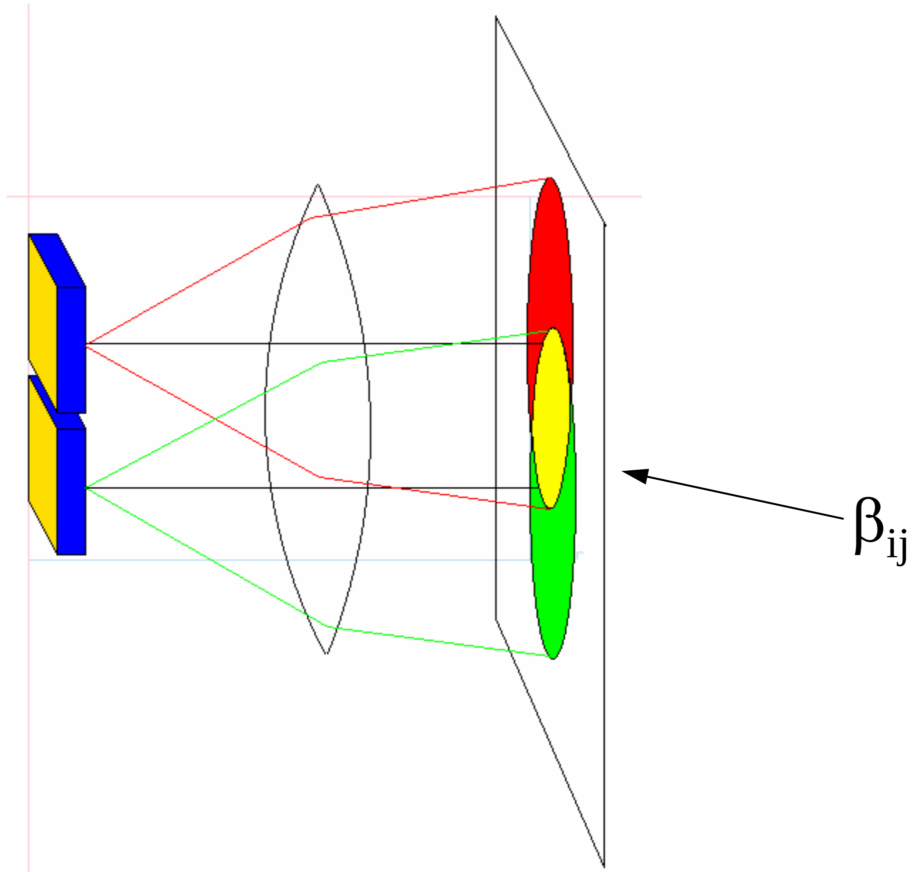
Wollack et al., 2006 – Future GBT Instrumentation Workshop

Pixel Coupling: Beam Overlap



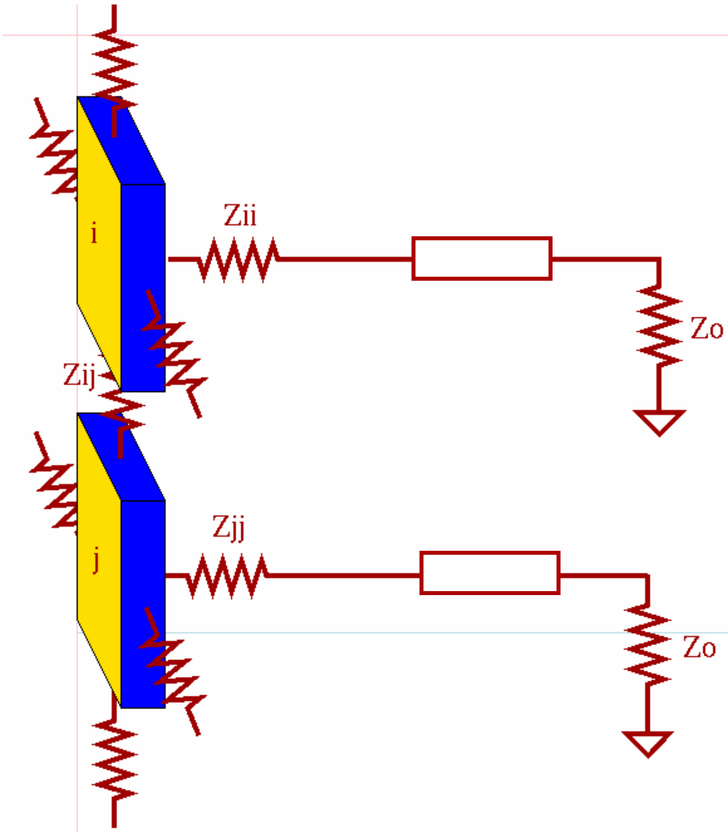
Wollack et al., 2006 – Future GBT Instrumentation Workshop

Pixel Coupling: Beam Overlap



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

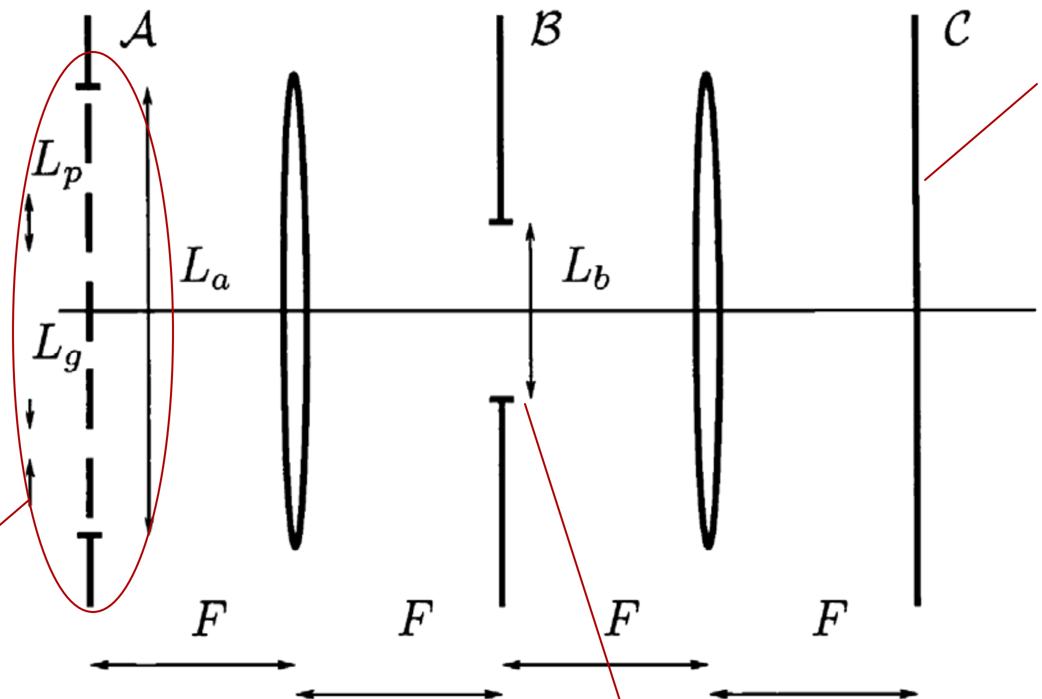
Pixel Coupling: Mutual Impedance



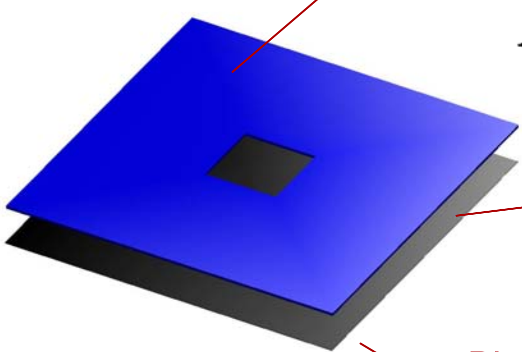
$$Z_m \approx \frac{2R_{rad} l^2}{r_{ij}\lambda_o} \sin\vartheta_i \sin\vartheta_j \exp\left(-j2\pi r_{ij}/\lambda_o\right)$$

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

Multimode Optical Response:



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



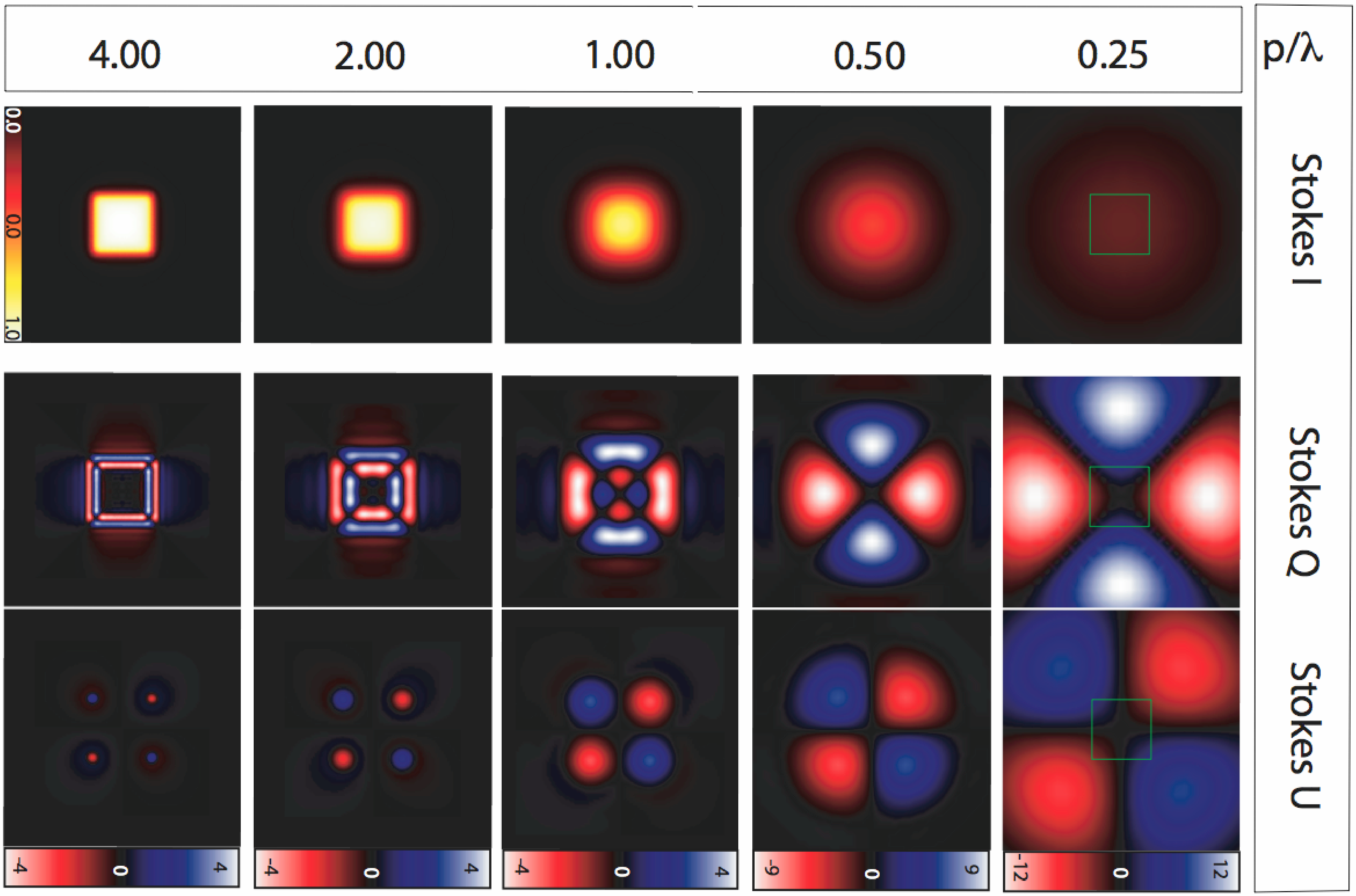
Bolometer is modeled by an aperture mask.

Pupil stop limits the number of modes processed by the optical system.Alternatively, L_b can be thought of as a spatial filter that limits transverse wave vectors to $<kL_b/2F$

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

Withington et al. 2003

Wollack et al., 2006 – Future GBT Instrumentation Workshop



Wollack et al., 2006 – Future GBT Instrumentation Workshop

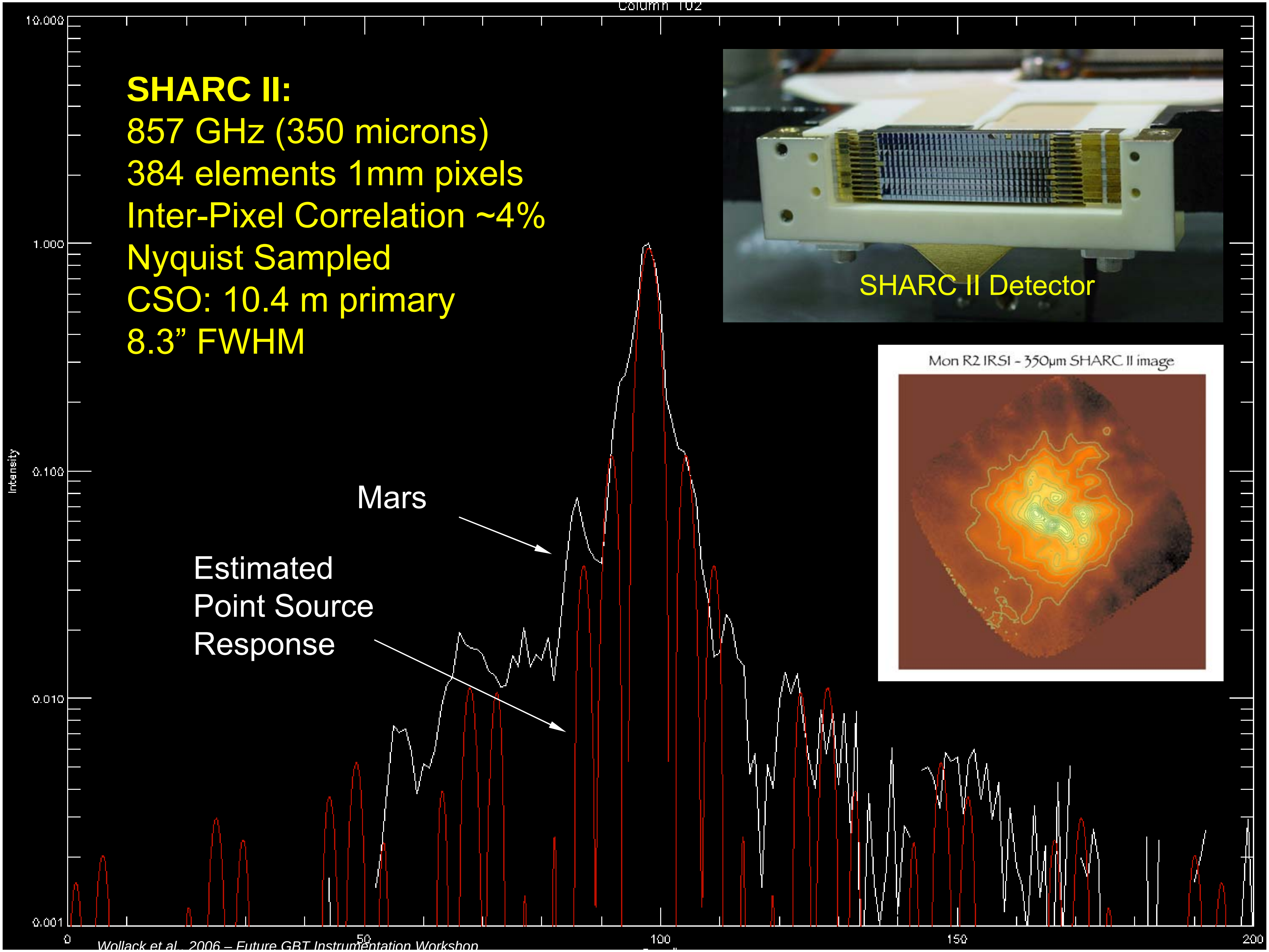
Polarization Response…

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 a millimeter wavelengths...

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

Solution	Loss	Reflections	Bandwidth	Fabrication
Symmetrize absorber (1-side)	+	+	-	+
Diagonal mesh (2-sides)	+	+	+	- -
Single polarization only	- -	- -	+	+
Absorb wave after absorber	- -	- -	+	- -
Polarizer in front of array	- -	- -	+	+
Rotating QWP	-	-	+	+
Rotating HWP	-	-	- -	+
Variable Delay Modulator	-	-	+	+

Wollack et al., 2006 – Future GBT Instrumentation Workshop


SHARC II:
857 GHz (350 microns)
384 elements 1mm pixels
Inter-Pixel Correlation ~4%
Nyquist Sampled
CSO: 10.4 m primary
8.3” FWHM
SHARC II Detector
Mon R2 IRS1 - 350μm SHARC II image
Mars
Estimated Point Source Response
Intensity
10.000
1.000
0.100
0.010
0.001
0
50
100
150
200
Wollack et al., 2006 – Future GBT Instrumentation Workshop