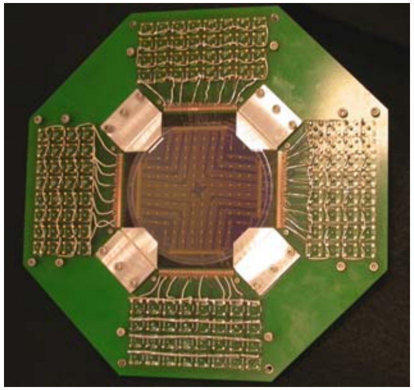

Terahertz Imaging and Security Applications

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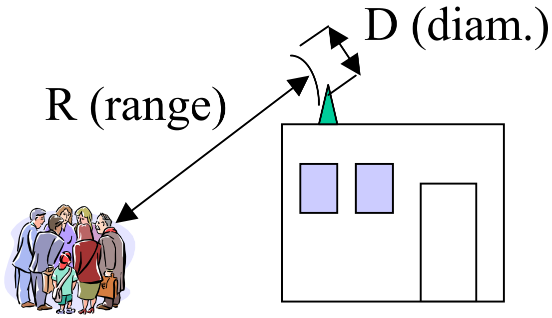
Outline

- Application
  - Concealed Weapons Detection scenarios
  - Penetration, spatial resolution, and other drivers for frequency range
- Detection schemes, background
  - Passive and active direct detection
  - Figures of merit, sensitivity limits
- Antenna-coupled microbolometers
  - Principle of operation, fabrication, characterization
  - Air-bridge microbolometers
- Single-pixel active imaging: phenomenology
- 2D Staring array : real-time video imaging
  - System description
  - Imaging results
- 1D scanned array : active real-time imaging with large field-of-view:
  - Active systems favor scanned architectures
  - System layout, component tests
  - Migration to 650 GHz
- Sb quantum tunneling diodes
  - Principle of operation, *I(V)* and noise properties
  - Prospects for passive direct detection
- Conclusions

Theme :
What can be done,
without major breakthoughs,
for large-format, real-time,
low-cost THz imaging ?

THz Imaging Arrays
Application Scenario



$$\text{Res} = (R/D)\,\lambda$$

- To image (detect and recognize) concealed threats
    - initially at short range (portal), e.g. 1.5 m
    - later at longer range, e.g. 10 – 50 m

Requires …

- <u>Diffraction-limited resolution and good transmittance</u>
    - D = 1 m (practical maximum) implies
    - res > 2.5 cm at 8 m range knife, gun, or explosive ?
      > 6 cm at 20 m
      > 15 cm at 50 m which person ?
    - this assumes f = 100 GHz (linear improvement with f)
    - Transmittance rolls off smoothly with increasing frequency (NIST measurements next page)

Optimal Frequency for Penetration

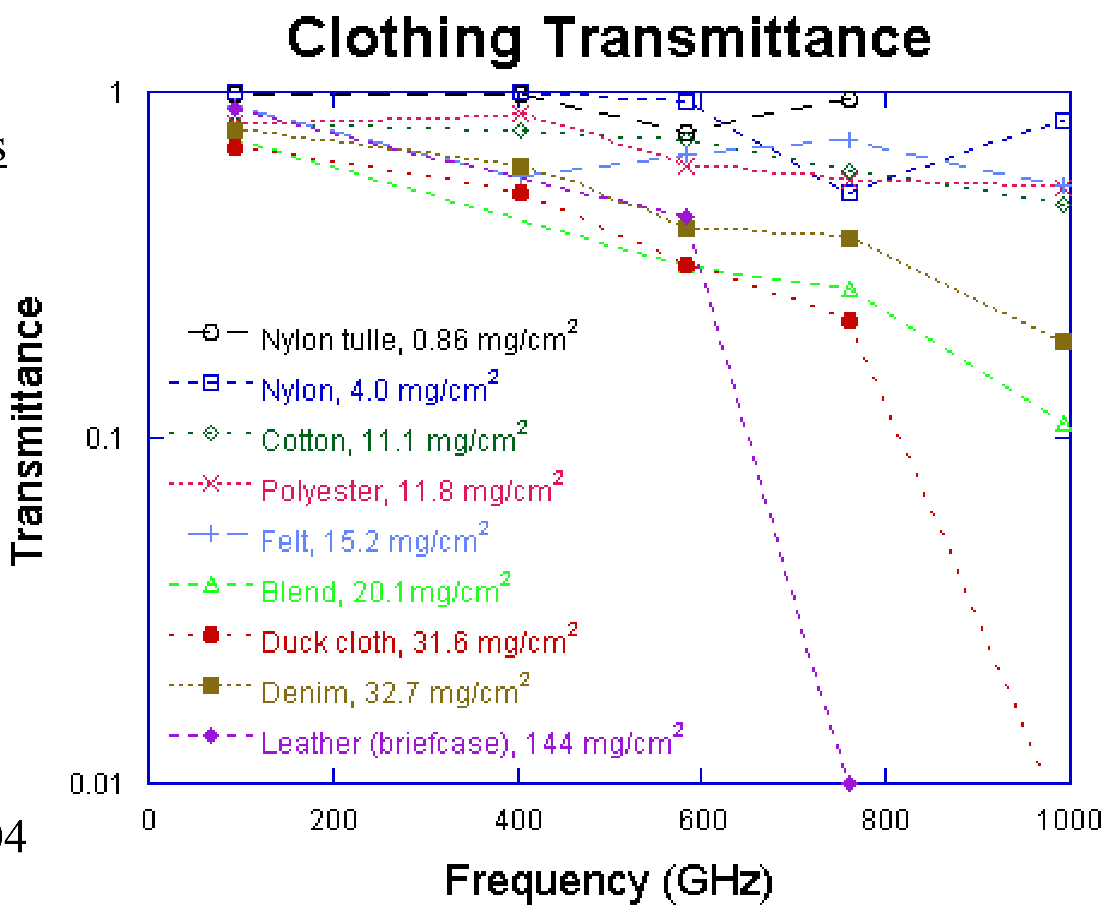
<u>Other 95 GHz measurements</u>

Goldsmith (93):
0.04 – 1 dB

Huegenin (96):
< 1 dB dry
3.5 dB wet

Sinclair (01) (40-150 GHz):
1 – 6 dB

See also Bjarnason et al. 2004 (THz and mid-IR)



From Grossman et al. Proc. SPIE, 2002

Application Requirements (cont.)

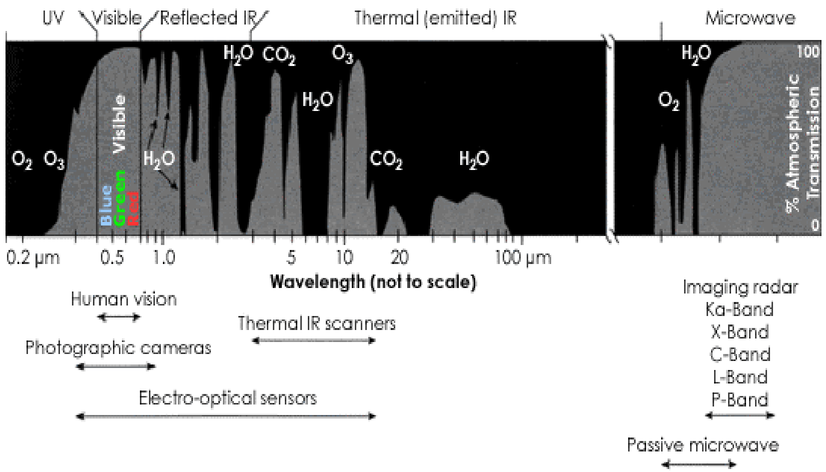
- Users care about
  - Image quality – i.e. resolution and sensitivity -> ROE curve
  - Throughput (speed)
  - Privacy (user-interface) and Safety
  - Footprint (in some cases)

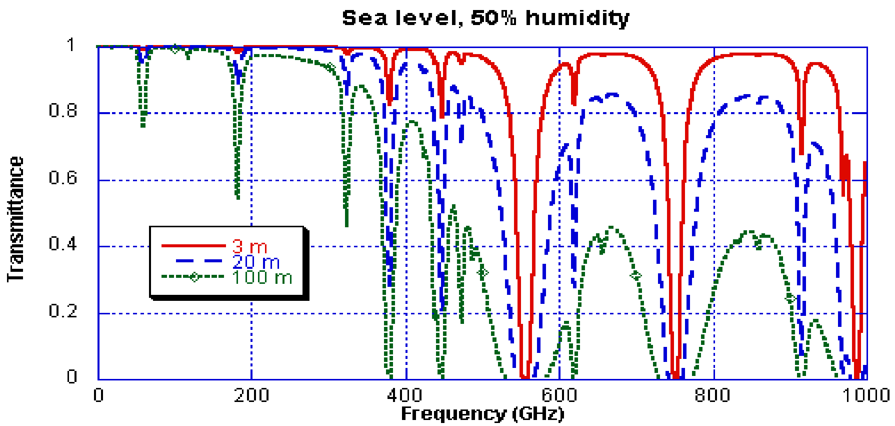
  - Range
  - Cost

- Technical drivers
  - Penetration and diffraction-limited resolution
  - Atmospheric transmission
  - Technological maturity

Atmospheric Transmission

- Swamped with rotational/vibrational spectra of molecules
- Terrestrial atmospheric transmission limited by H_2O absorption to a few windows (3 mm, 2 mm, 1.3 mm, 0.85 mm, 0.45 mm, 0.35 mm) for long ranges
- 1/e absorption length is comparable to range for many interesting applications, i.e. 10's of m





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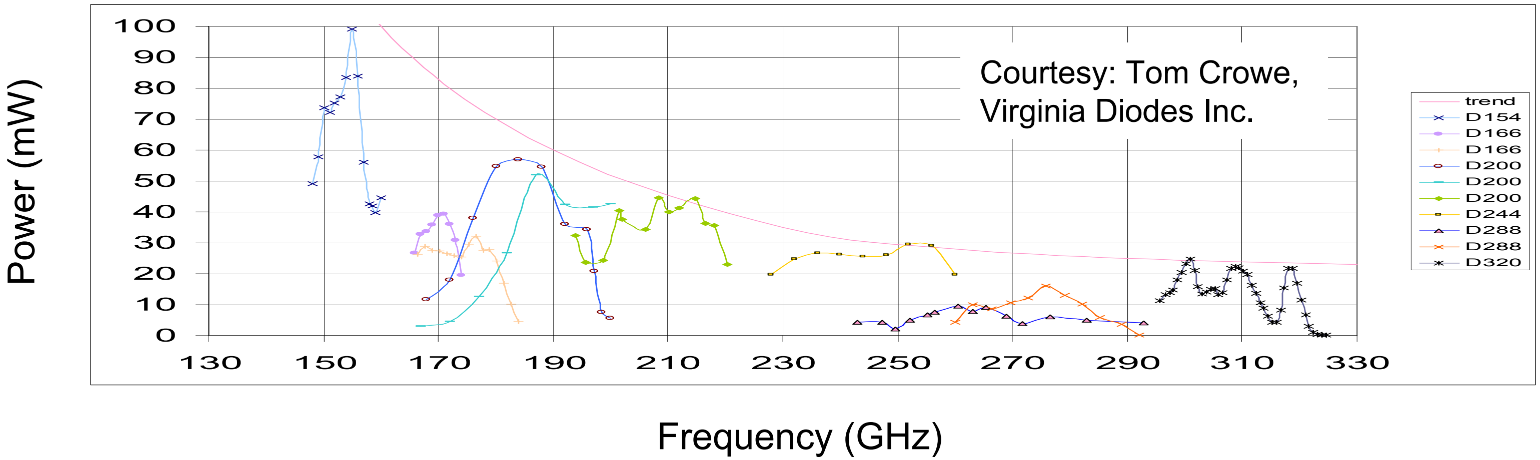
Technological Maturity, esp. Sources

- Fundamental W-band (Impatt and Gunn diode) sources show P ~ 1/duty cycle
  - expected for thermally limited devices

~300 mW CW ~15 W pulsed (d=.5%) (Quinstar)



- High efficiency varactors may show opposite behavior; key for migration of active systems to THz range

Duty cycle	Output power at 70 GHz (W)	Efficiency (%)	$P_{out} * D^{1/2}$ (W)
CW	1.4 W	17.5	1.4
10 %	2.0 W	25	0.63
4 %	2.7 W	33.8	0.54
2 %	3.1 W	38.8	0.44

Initial VDI 600 GHz varactor chain
Peak power 1.2 mW at 640 GHz

Data courtesy T. Crowe, Virginia Diodes Inc.

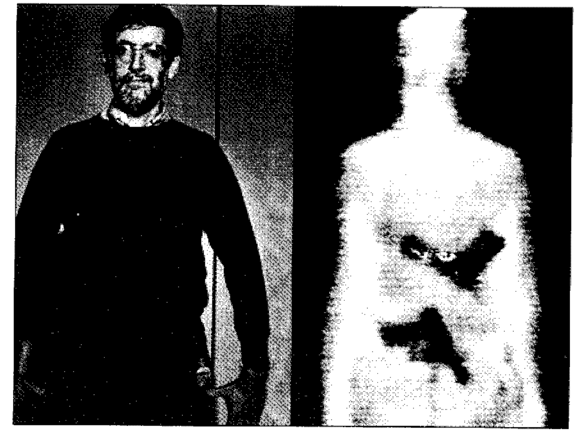
PMMW is old-hat, isn't it ?

- Single pixel scanned image
- 30 minutes acquisition time
- Since 2001, realtime readout

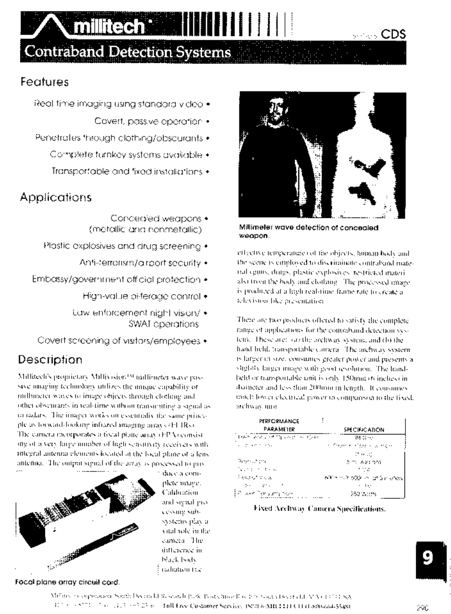
available on some systems

- Sensitivity (500 – 5000 K)

"fixed" This is 0.1 – 1 % of quantum limit, a practical limit for uncooled receivers



Millimeter wave detection of concealed weapon.


millitech

series CDS

Contraband Detection Systems

Features

- Real time imaging using standard video
- Covert, passive operation
- Penetrates through clothing/obscurants
- Complete turnkey systems available
- Transportable and fixed installations

Applications

- Concealed weapons (metallic and nonmetallic)
- Plastic explosives and drug screening
- Anti-terrorism/airport security
- Embassy/government official protection
- High-value pilferage control
- Law enforcement night vision/ SWAT operations
- Covert screening of visitors/employees

Description

Millimeter wave detection of concealed weapon.

Focal plane array circuit card.

Fixed Archway Camera Specifications.

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- 1995: Millitech catalog

Active vs Passive Imaging - Sensitivity

- Passive mmw signals are small; This is much harder than in IR

  - For f=100 GHz, bandwidth=100 GHz, 1 diffraction-limited pixel :

  Total power = 400 pW :
  Outdoor contrasts are ~ 200 pW
  BUT Indoor contrasts are < 10 pW

  } This is fundamental, P=kTB

- To detect < 1 pW in 1/30 s with S/N=10, you need
  either cryogenic detection (NEP=$3x10^{-14}$)
  or coherent detection (Tnoise=12,000 K)
  - coherent detection is complex and expensive

$$1\sigma = \frac{NEP}{\eta\sqrt{2\tau}}$$

- 100 GHz worth of indoor blackbody emission 1.4 pW/ K

$ 5000 active source 10 mW

-Active imaging should be easy, even with incoherent detection

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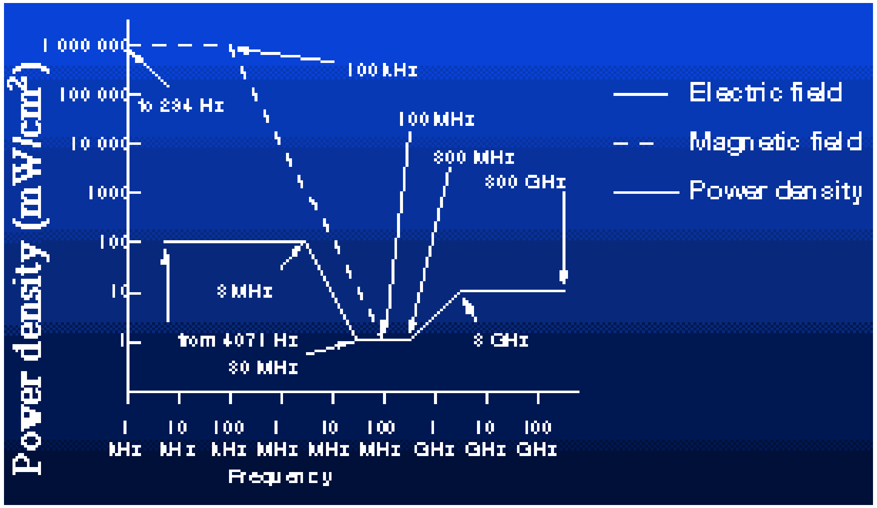
Colloquium, Sandia Natl. Lab, 11/17/04

What about Safety ?

• FCC Ruling based on ANSI/IEEE standard C95.1-1992, for 100 GHz

1.0 mW/cm^2 (general public) 5.0 mW/cm^2 (controlled access)

Occupational (controlled access) field strength limits



Not an issue for mmw or THz active imaging;
100 mW across 1 m^2 body area is x100 below guideline

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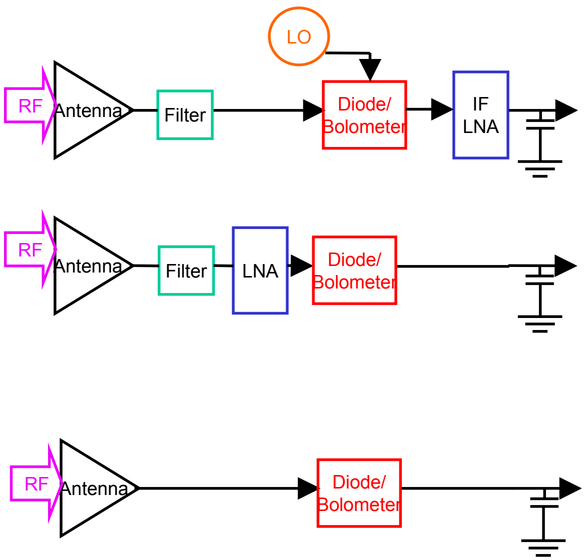
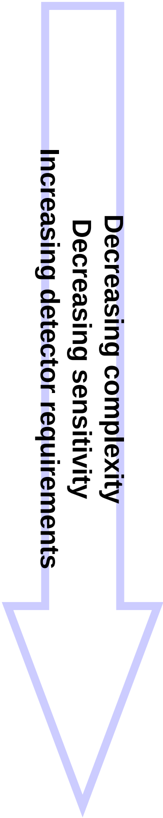
THz Detection: technology matrix

- (Passive) kilopixel imaging at video rates at mm/sub-mm waves



Technology	Sensitivity	Price
Coherent heterodyne	**Good**	**Huge**
Coherent direct (with preamplification)	**Good**	**Large**
Incoherent direct (no preamplification)	***Moderate***	***Small***
Antenna coupled microbolometers	**Poor (active only)**	**Tiny**



Maximum frequency

~200 GHz	**600 GHz**	**> 1THz**

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Figures of merit (Passive detection)

- For direct (incoherent) detectors, typically *Noise Equivalent Power* (NEP) [W/Hz$^{1/2}$]

$$\mathrm{SNR} = \frac{\eta P_{sig}}{NEP_e}\sqrt{2\tau_{\mathrm{int}}}$$

- For coherent heterodyne typically expressed as *noise temperature*

$$T_N = \frac{NEP}{k_B\sqrt{\Delta\nu}}, [\mathrm{K}]$$

- For passive detection of thermal (continuum) targets, *Noise Equivalent Temperature Difference* (NETD) is most useful (includes detection bandwidth)

In Rayleigh- Jeans limit

$$NETD = \frac{NEP}{\partial P/\partial T_{\mathrm{target}}\sqrt{2\tau_{\mathrm{int}}}} \approx \frac{NEP}{nk_B\Delta\nu\sqrt{2\tau_{\mathrm{int}}}}, [\mathrm{K}]$$

- With active illumination, the most useful FOM is *Noise Equivalent Reflectance Difference* (NERD)

$$NERD = \frac{\sigma_p}{P_{pp}} = \left(\frac{NEP}{P}\right)\left(\frac{8L^2}{D^2}\right)\frac{N_{pix}}{\varepsilon_s R(2\tau)^{1/2}}$$

Distance

Aperture diaam.

average reflectance

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Antenna-coupled Microbolometers

Antenna-coupled microbolometers

- A thermally isolated, resistive termination for a lithographed antenna
- Signal coupled to the bolometer changes its temperature: $\Delta T = P_{inc}/G$
- A DC current is used to sense the resistance of the bolometer, given by $R = R_0(1+\alpha\Delta T) \equiv R_0(1+\beta I^2)$
- Electrical responsivity $S_e = \beta I$
- Noise contributions:
  - Phonon noise
  - Johnson noise
  - 1/f noise
  - Amplifier noise

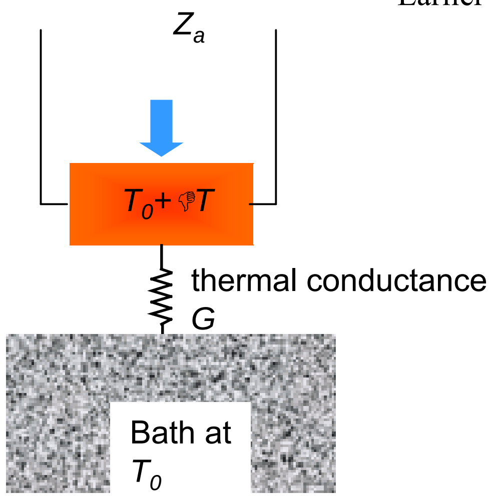
- For room temperature devices, NEP is limited by Johnson noise

Earlier work on ACMBs

Tong 1983

Rebeiz 1990

Hu 1996



$$NEP_e = \frac{\sqrt{4k_B T^2 G}}{\alpha\sqrt{\Delta T_{bias}}}$$

NIST

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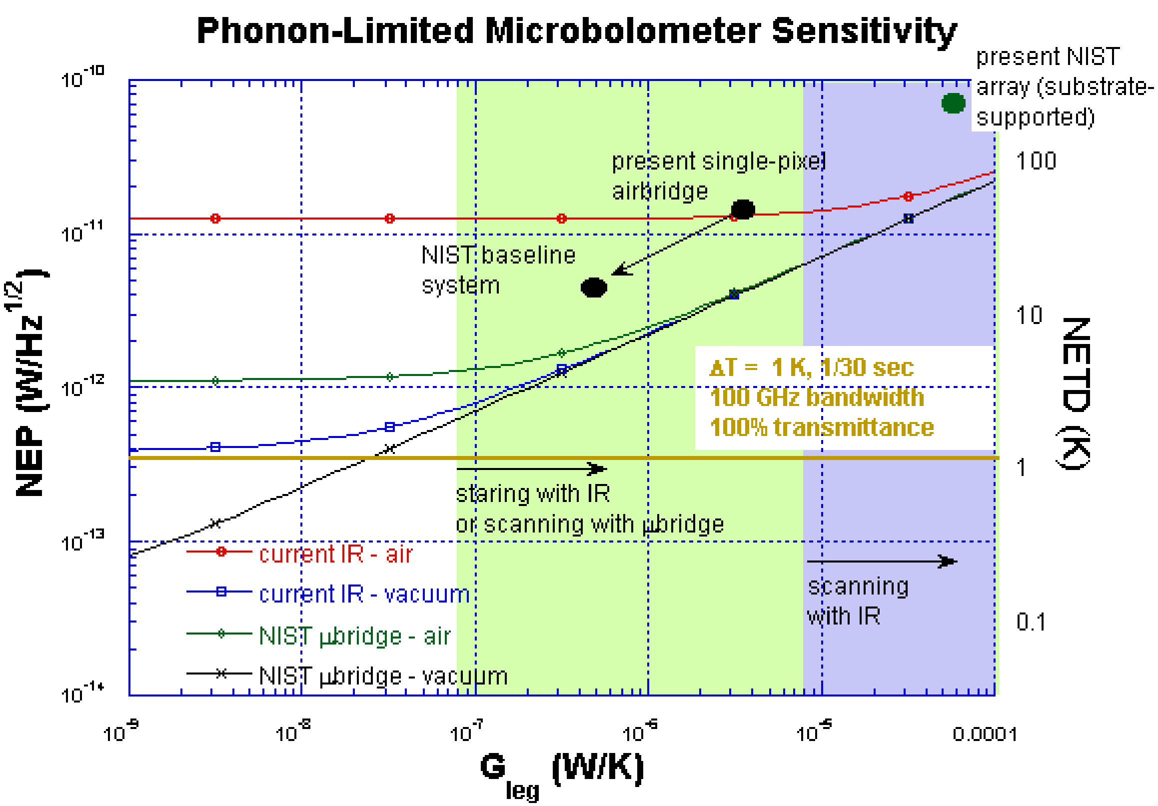
Microbolometer Sensitivity Limits

- For <u>passive</u> imaging, ACMB's lack the necessary sensitivity



How the calculation works:

P_{min} = NEP/sqrt(2τ)

NEP = sqrt($4kT^2G$)

$G = G_{dev} + G_{air} + G_{rad}$

G_{air} = (.025 W/m-K)A/L

G_{rad} = dP/dT where

$P=\sigma T^4 A$ or $\pi^2 k^2 T^2/6h$

(multimode or single-mode)

For current IR,

A=50x50 μm,

L = 2.5 μm (current) or

50 μm (high aspect)

For NIST microbridge,

A=2x10 μm,

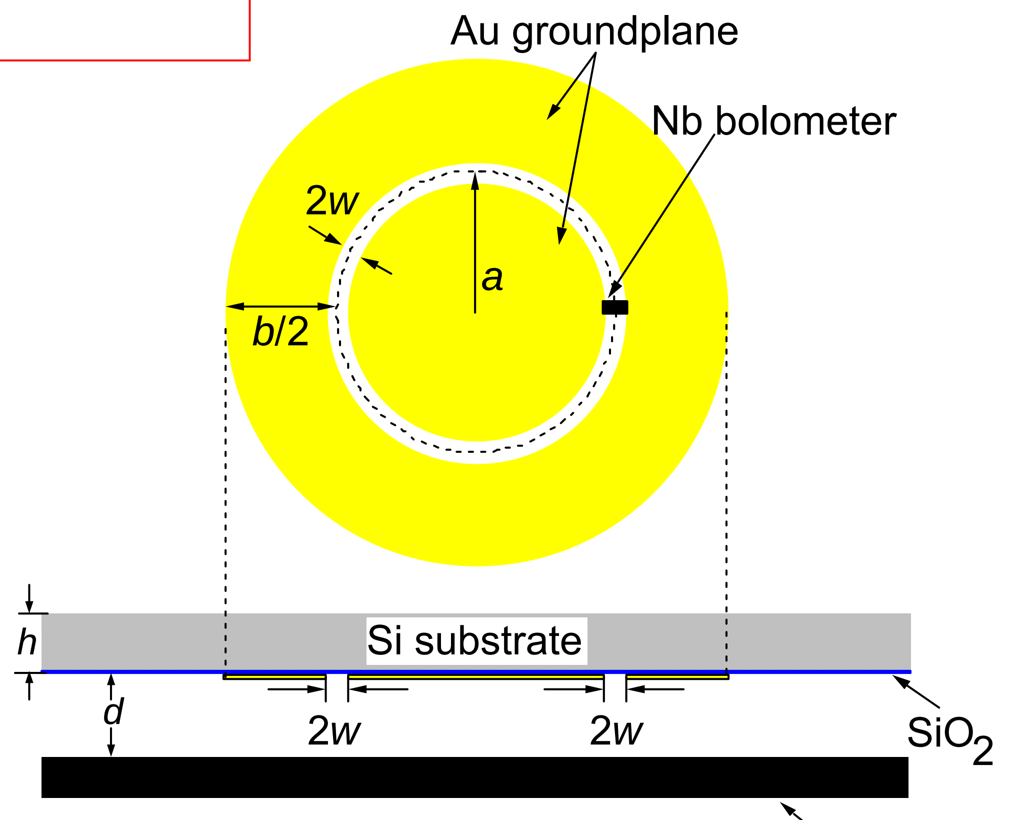
L = 2 μm

Slot-ring Antenna Configuration

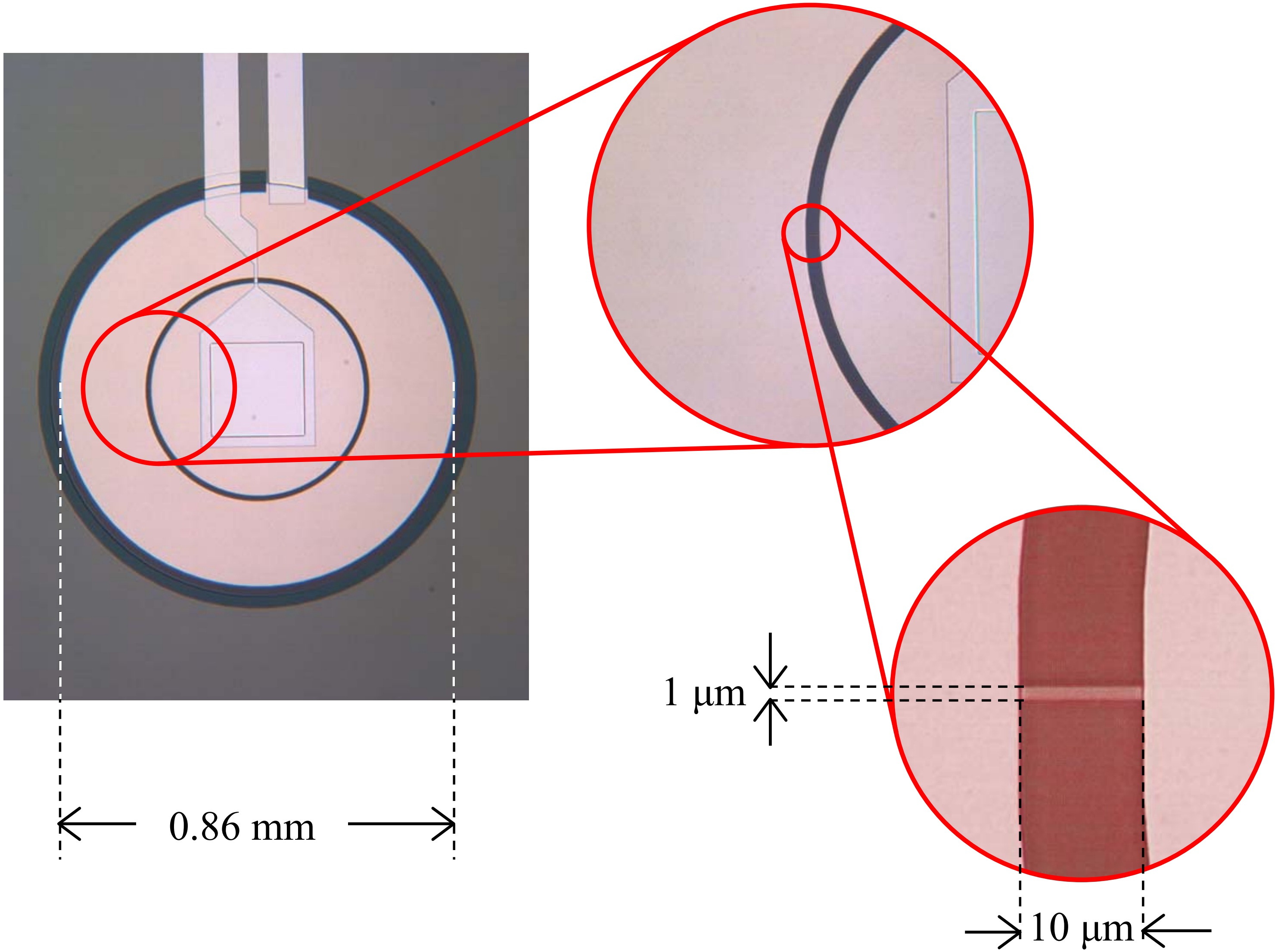
The problem : High efficiency mmw feed antennas are generally not array-compatible

- Large-format array precludes substrate lenses or horns
- Slot transmission line; circumference = λ_{guide}
- Electrically thin substrate
  h < $\lambda_{dielectric}$ / 20 (= 50µm)

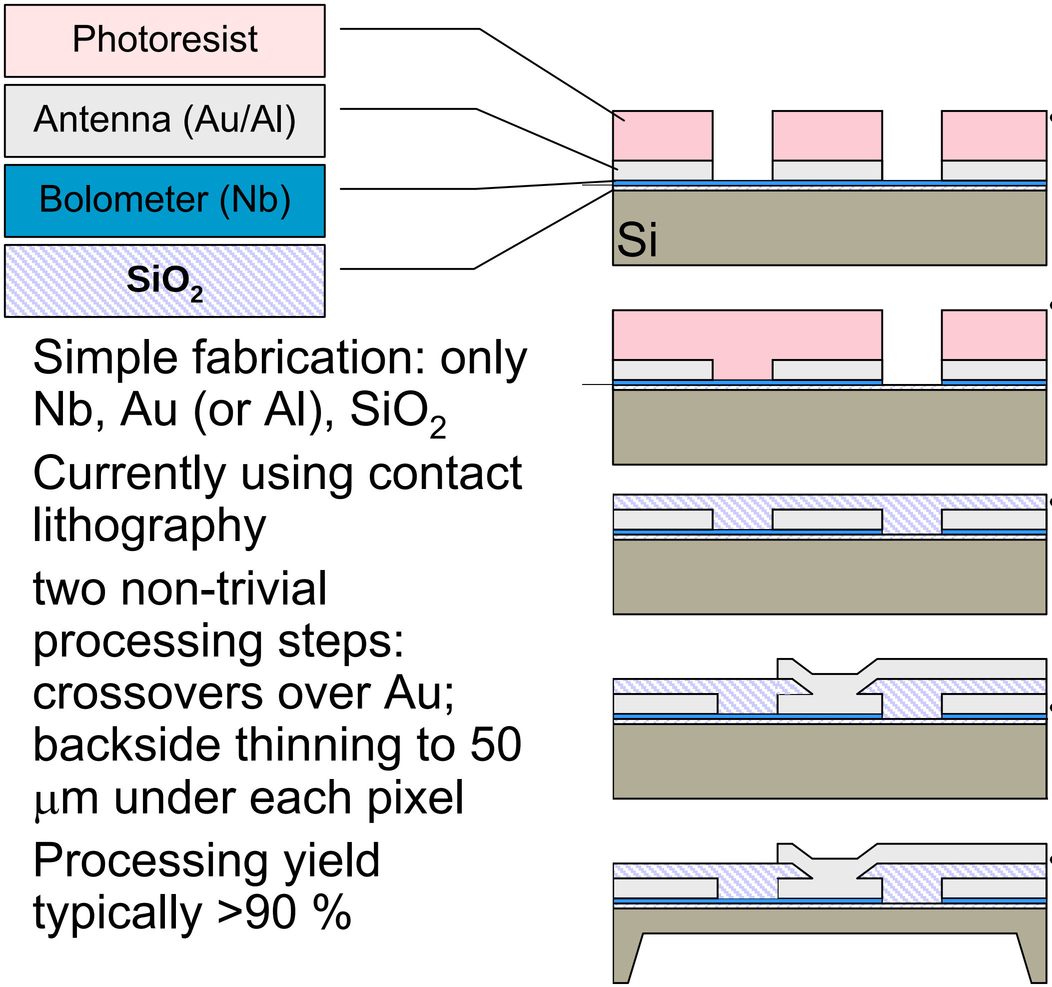
- $3\lambda_0/4$ backshort to raise directivity and recover backside coupling
  - -3 dB beamwidth = 21°
  - antenna impedance
    103-48j Ω



Substrate-Supported ACMB



FPA fabrication



- Simple fabrication: only Nb, Au (or Al), SiO_2
- Currently using contact lithography
- two non-trivial processing steps: crossovers over Au; backside thinning to 50 μm under each pixel
- Processing yield typically >90 %

- Deposit bolometer-antenna bilayer, spin & pattern photoresist mask, define slot
- Pattern photoresist mask, remove Au from on top of the bolometer
- Deposit SiO_2 for cross-overs
- Define vias through the SiO_2, deposit top wiring
- Perform backside etch of Si under each pixel

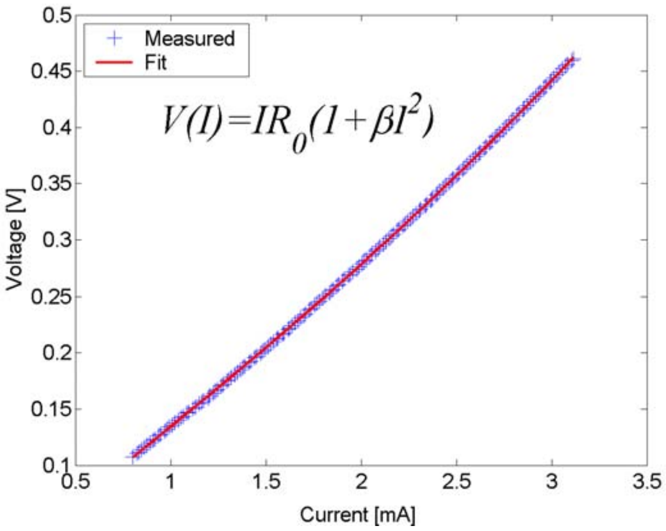
FPA Characterization

• Physics of self-heated bolometers extremely well understood

• Readout electronics allow for the simultaneous measurement of all 120 V(I) curves; Fit to the V(I) gives R_0, specific responsivity β [V/W/mA]

•Compared to Vox, Nb is lower responsivity but also lower noise

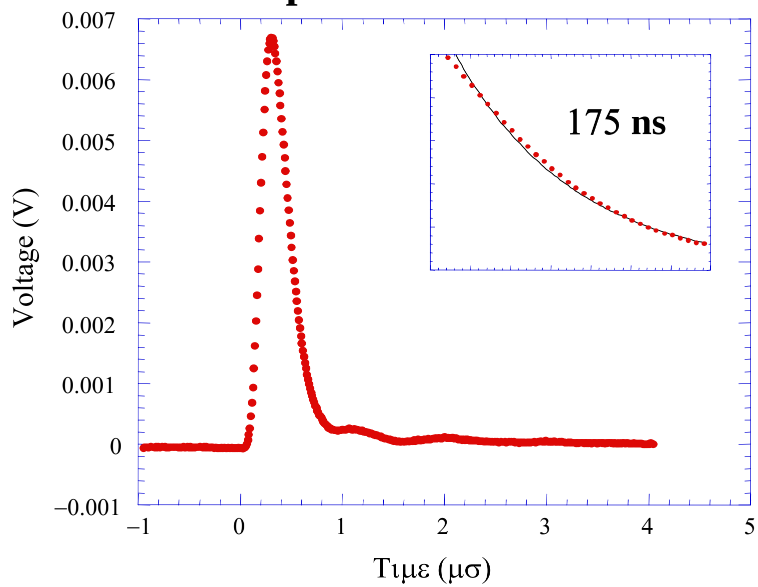
- Electrical:
  - V(I) curves of all pixels
  - Noise
  - Uniformity
- Optical
  - Efficiency
  - Polarization response
  - Speed



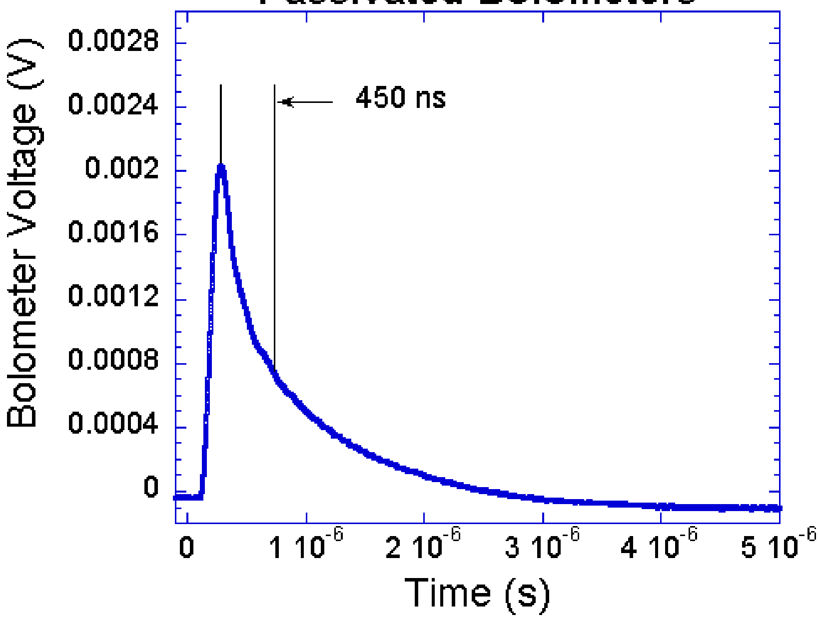
Passivated bolometer properties

- Oxidation is much slower, bolometers can be biased hotter
- Approximately x 8 higher optical responsivity
- Response is somewhat slower

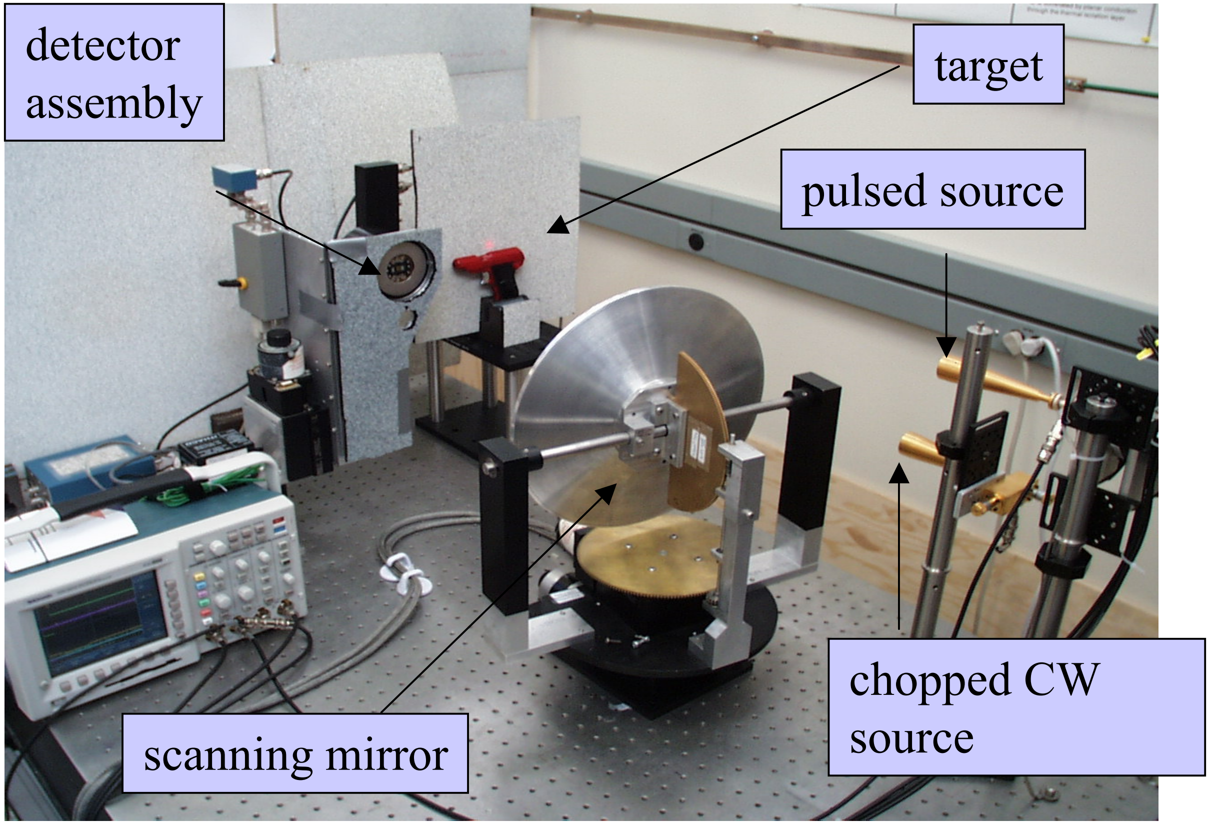
Single chip, exposed bolometers



Micromachined Array, Passivated Bolometers

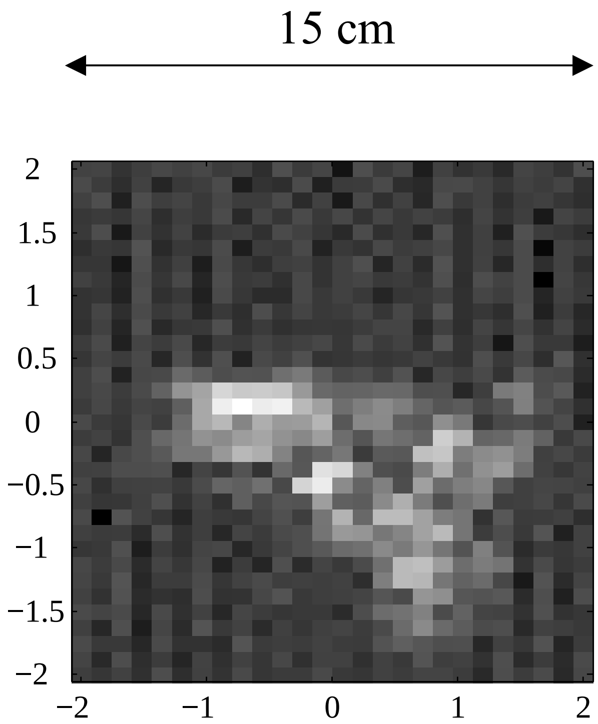


Scanned Imaging System



- Image acquired in 20 s, limited by mechanical stage
- Goal : qualify system (target reflectance, spatial resolution, sensitivity, etc.), examine phenomenology

Gun Images (rev. 2 optics)



Conclusion #1 : Unpredictable hotspots

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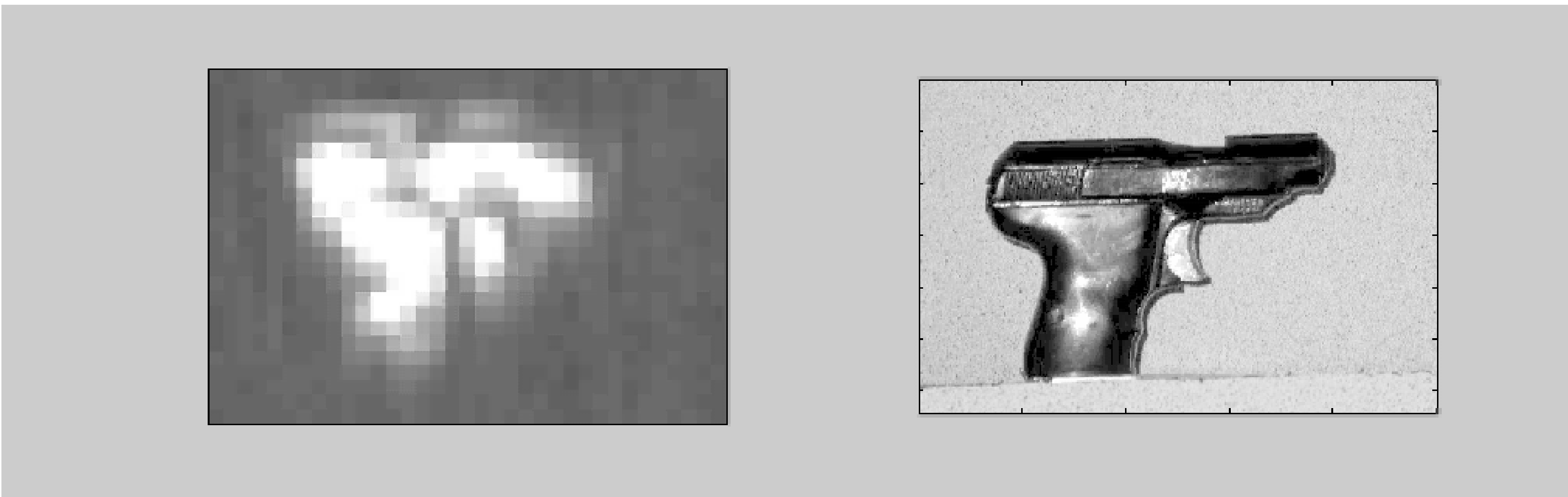
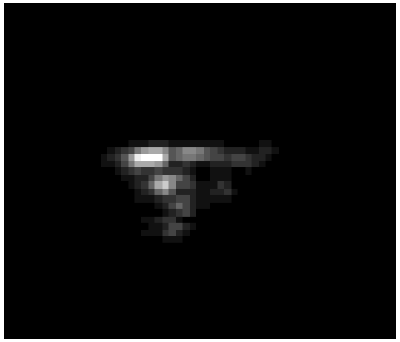
Colloquium, Sandia Natl. Lab, 11/17/04

Gun Rotation Movie



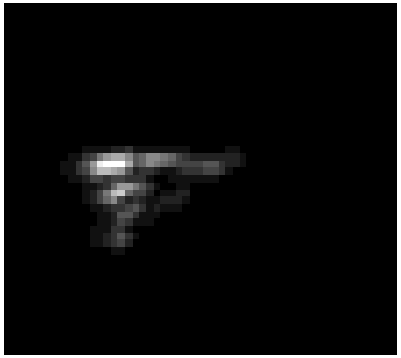
Compare Illumination Modes

CW Illumination



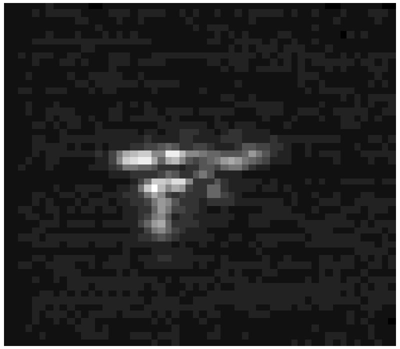
370

FMCW Illumination



400

Pulsed Illumination



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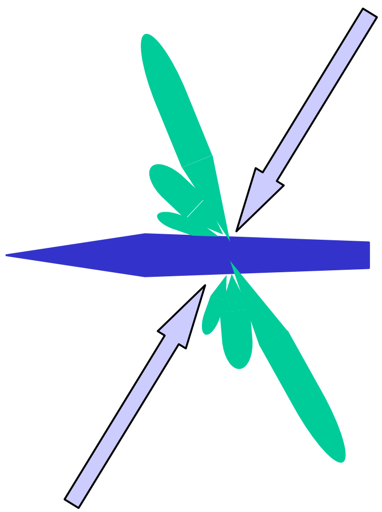
Dynamic Range
(Peak/noise)

Conclusion #3 : Illumination mode (temporal) has little influence on qualitative image quality.

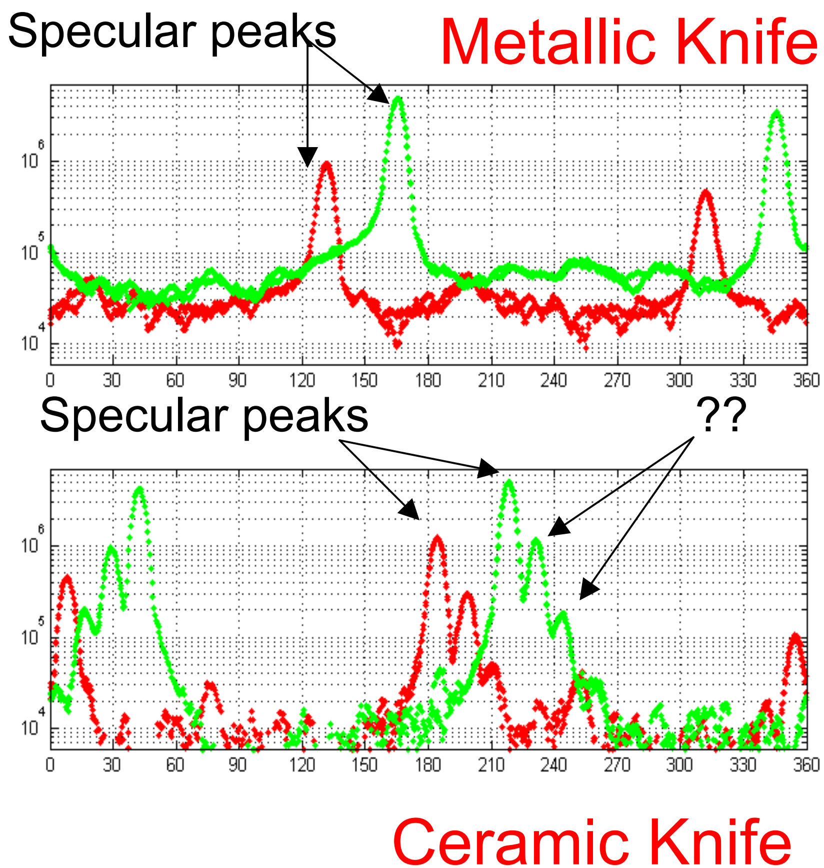
Video imagery: observations

- Some objects show surprising features:

Top View



Non-specular peaks are not rotationalsly symmetric, but have k diplaced toward edge



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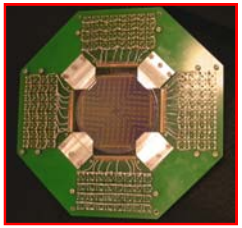
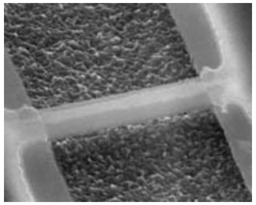
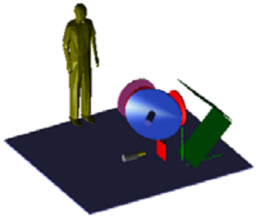
Active THz Imaging Arrays

program directions, milestones

	Format	NEP	Speed	Status
95 GHz, staring FPA (Luukanen 5410-29)	120-element (12x12 less corners)	80 $pW/Hz^{1/2}$ (elec.) 6-30 % effic.	400 kHz	In use (phenomenology)
95 GHz, Airbridge (Miller 5411-04)	Single-pixel	20 $pW/Hz^{1/2}$	30 kHz	Testing prior to insertion in scanned arrays
scanning FPA 95 GHz (Grossman 5411-09)	128 detector X 300 scanpositions	20 $pW/Hz^{1/2}$ (elec.)		Under construction
650 GHz				proposed







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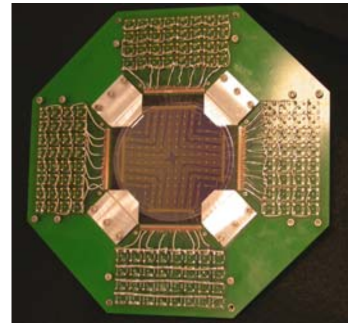
Antenna-coupled Microbolometer Arrays

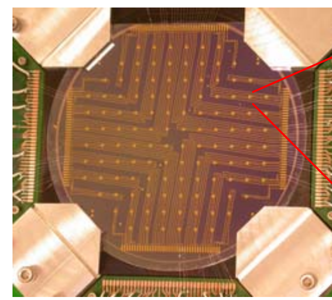
- ACMB arrays are simple and cheap
  - 4 mask layers + 1 backside etch
  - no semiconductors
  - Si substrates (large diam. possible)



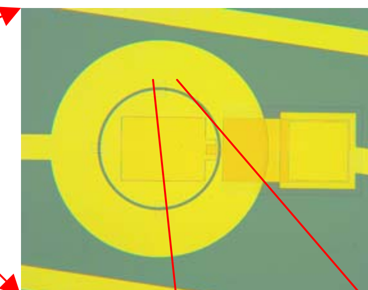
•Prior mmw ACMB arrays
- Tong (1983)
- Rebeiz (1990)
- Hu (1996)

and many others

- ACMB arrays are frequency extensible
  - microantenna alone to > 30THz
  - substrate thickness dominates design

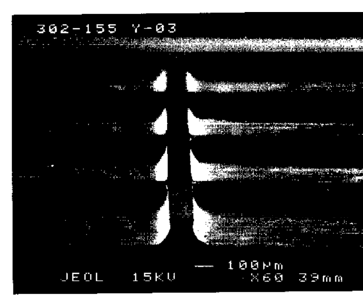


4.75 mm array pitch



1.6 x 10 x .02 µm bolometer

- ACMB performance is adequate for active systems
  - NEP ~ 50-100 pW/Hz1/2
  - Speed ~ 400 kHz
  - pixel count limited by real estate, now ~ 100



160 µm

55 µm

• This speed can be traded for pixel count via scanning

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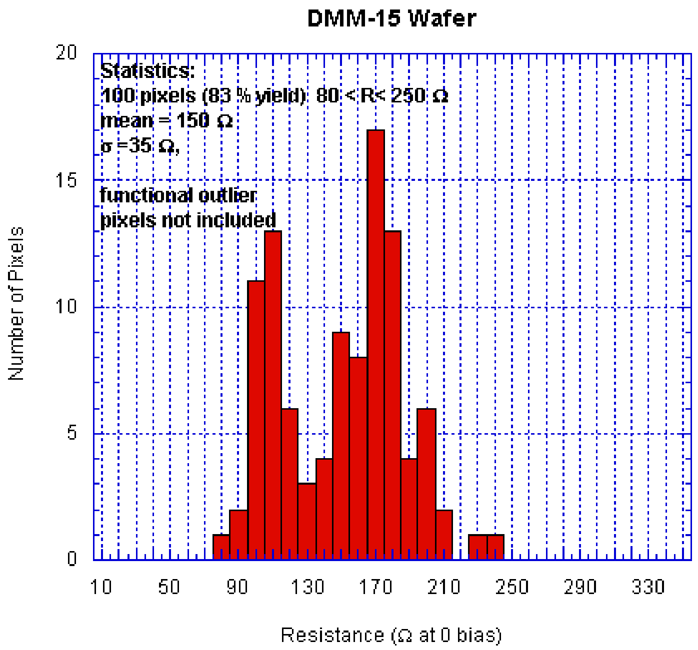
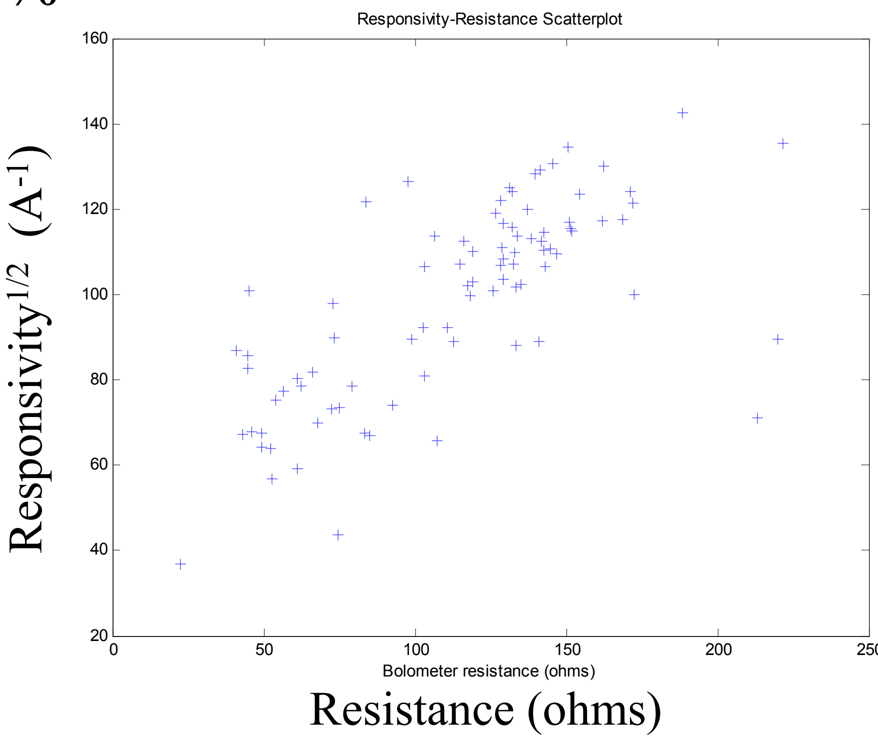
Array Uniformity

- Current FPA's show +/- 39 % (1 σ) uniformity in R
- Correlation between R and Responsivity indicates nonuniformity is limited by linewidth variation
- Optical "flat-fielding" indicated
- Conversion to projection lithography has improved the *R*- nonuniformity to ~ 5%





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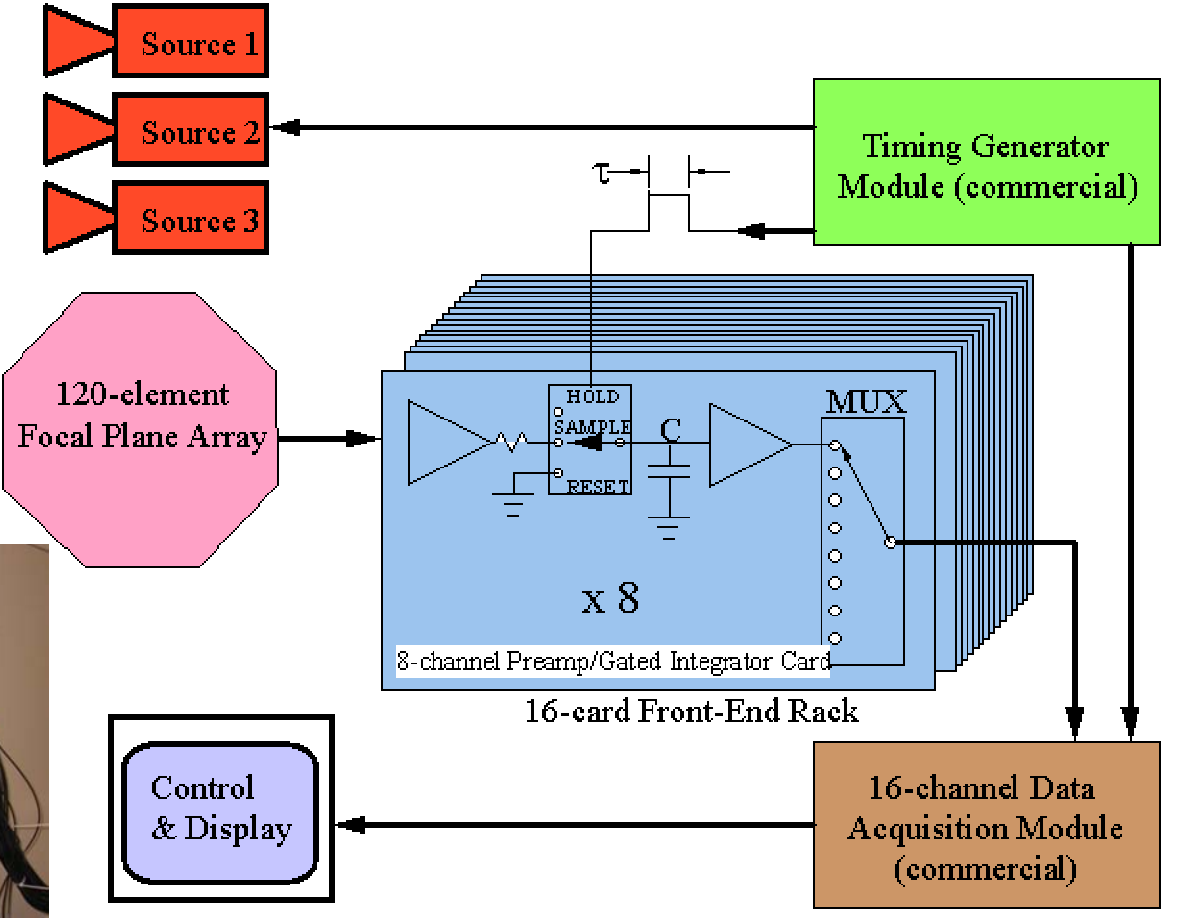
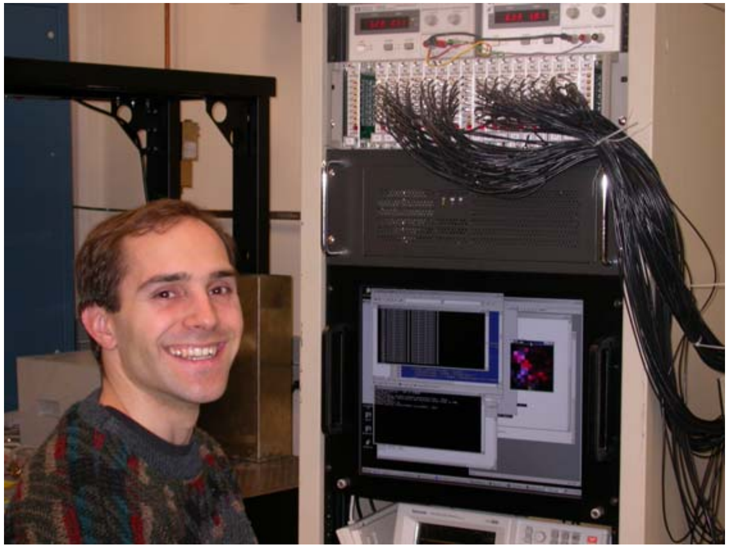
Active Imaging System Block Diagram

- “Brute-force” repetition of 120 channels amplification and gated integration (8 chan. per card
- Real-time readout
- ASIC-able





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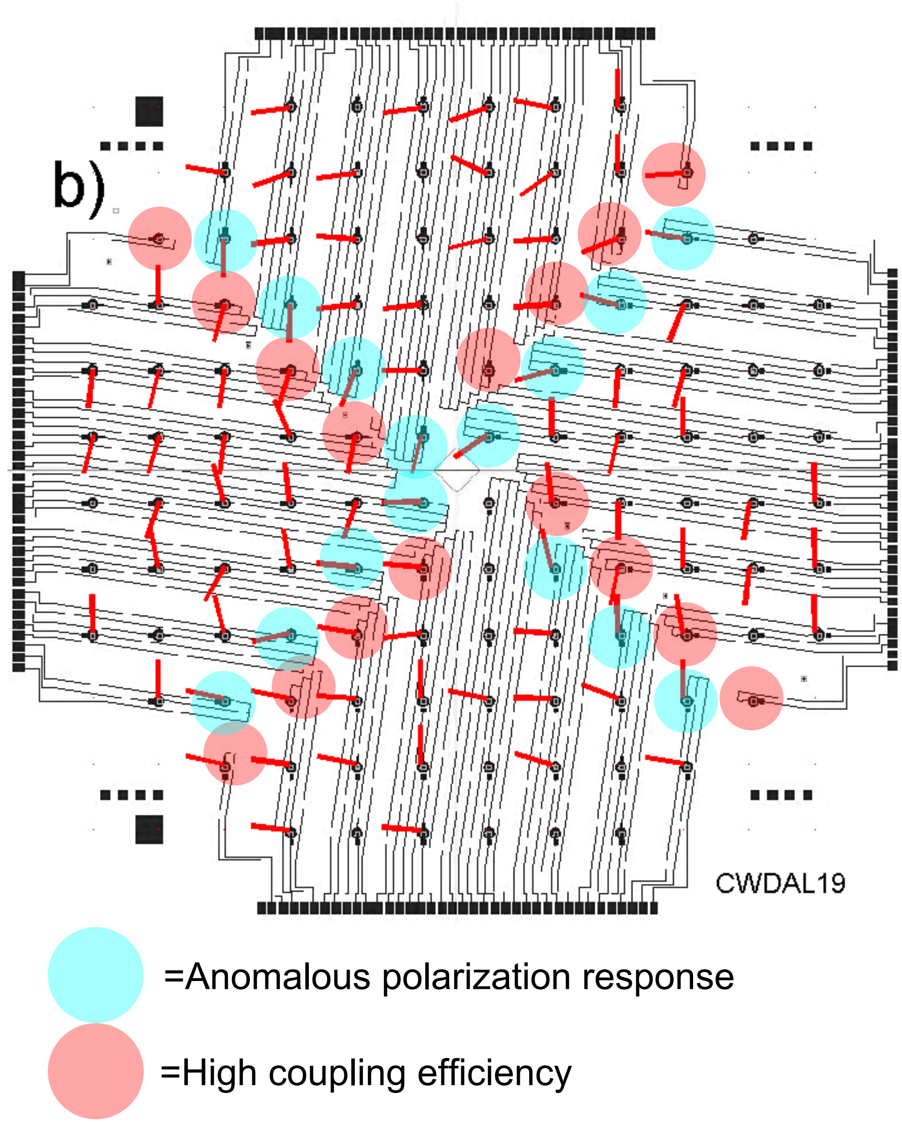
FPA Optical characterization

- Polarization measurement carried out by rotating a source 180°, while acquiring a ‘movie’ with the FPA
- Pixels at the CCW edge show anomalous polarization response
- May be due to coupling to the straight section at the end of these bias circuits
- However, unless this effects the pixel to pixel cross-talk, effect can be corrected using flat field measurements for both polarizations
- These pixels are not the same as the ones showing high coupling efficiency



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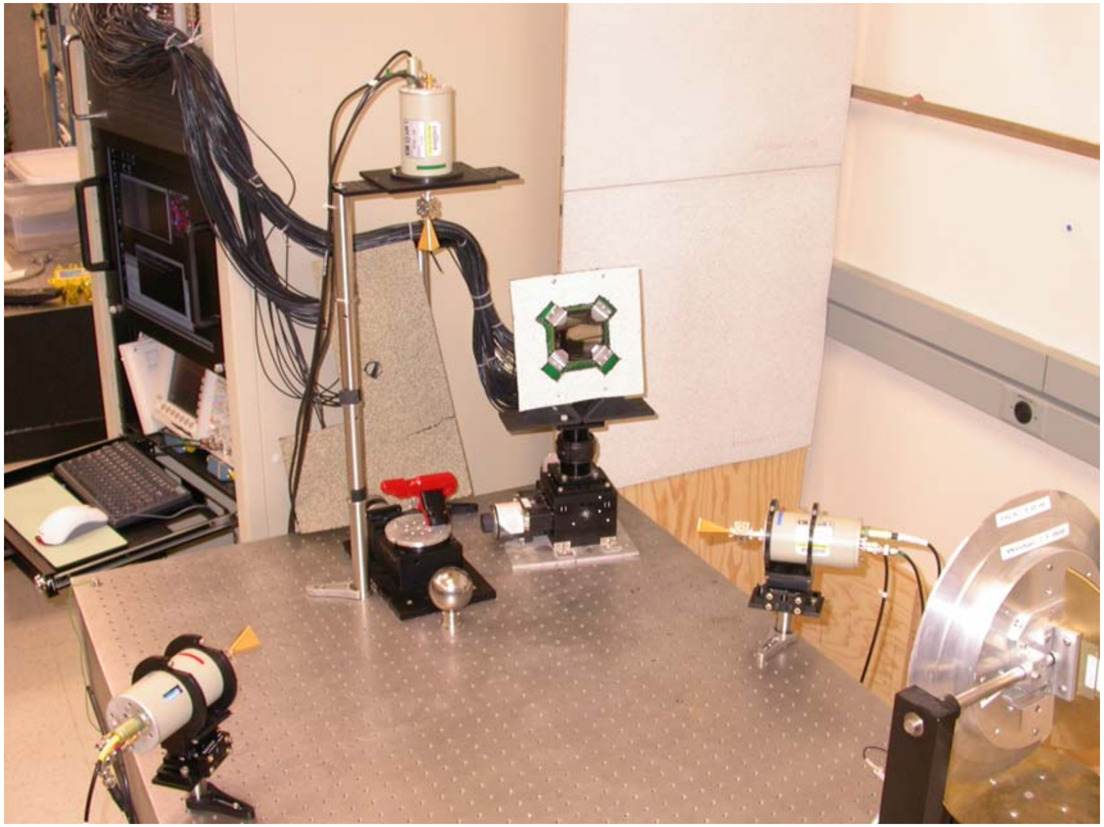
3-D Illumination System

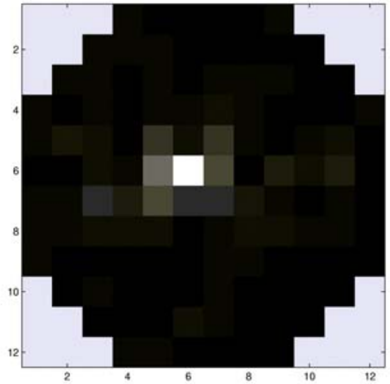
- Illuminate from X, Y, and Z directions

- Detect from (1,1,1) Direction

- 1 m radius spherical collecting mirror, at unity magnification

- Source pulse trains are interlaced in time

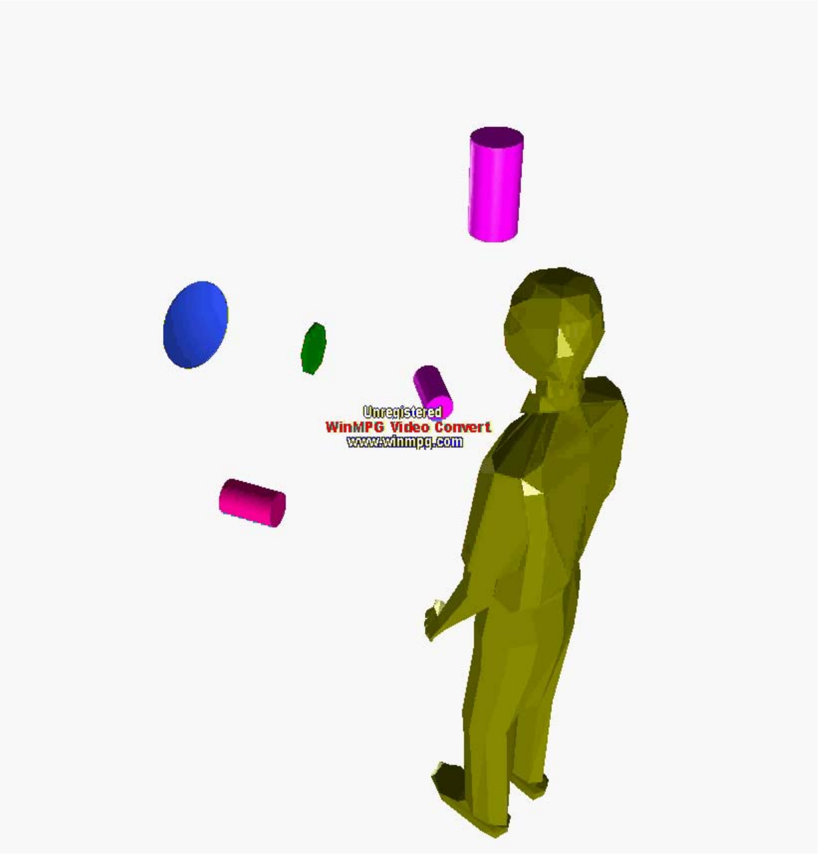




Map of point source (open ended WR-10)

Video imagery

- Video imagery acquired for various objects
- A stream file allows for post processing of the videos
- Color coding of the three sources facilitates image interpretation
- Polarization of sources set to 45° in order to obtain signal from all FPA quadrants



Video imagery: point source movie

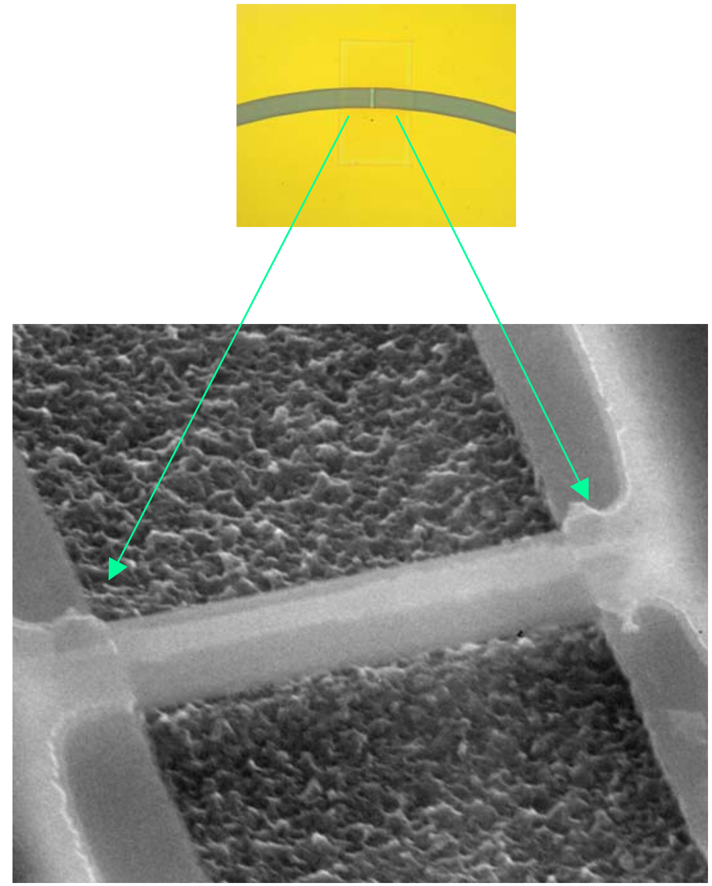
Video deleted for size

Video imagery: Suicide bomber

Video deleted for size

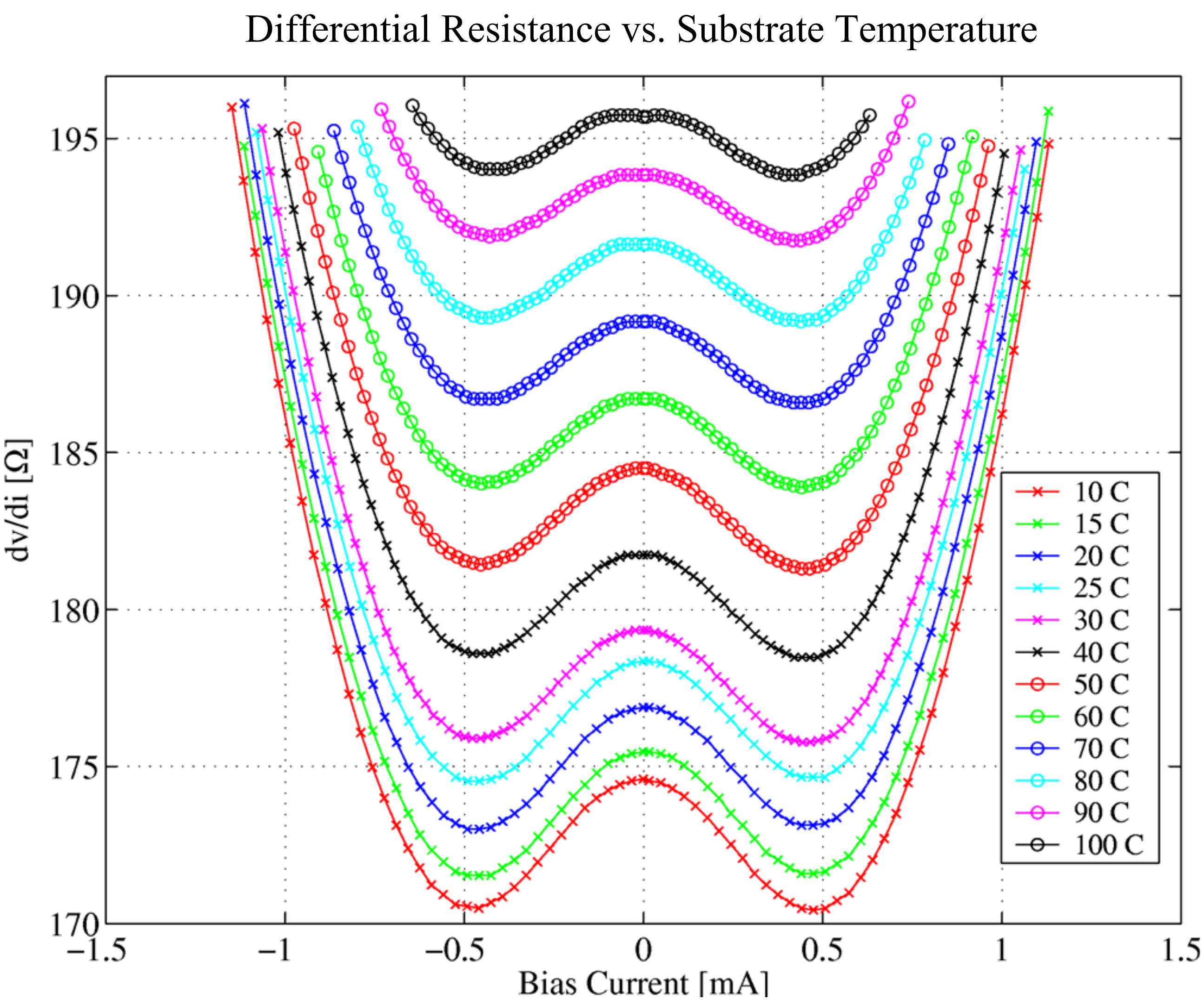
Airbridge Microbolometers

- Current FPA microbolometers
  - 5-10 V/W-mA
  - 25-50 V/W
  - 400 kHz
- Airbridge
  - 40 – 80 V/W-mA
  - 100 V/W
  - 50 kHz (est.)
- Optimum (for 1D scanned system)
  - maximize V/W consistent with
  - ~ 20-40 kHz bandwidth



10 micron airbridge,
Nb strip passivated in SiO_2,
Released with XeF_2 etch
Of underlying Si

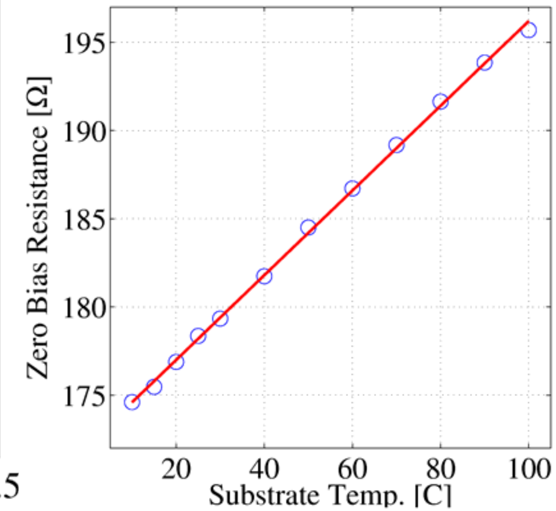
Air-Bridge dv/di vs. T



- **Al antenna metal**
- Maximum $I_{bias} \approx 1.7$ mA
- $G = 4.5$ μW/K
- Johnson-noise limited

□ $\tau \approx 4$ μs

- $TCR = 0.13$ % per degree K
- $\beta = 54$ V/(W·mA)
- Responsivity = 86 V/W



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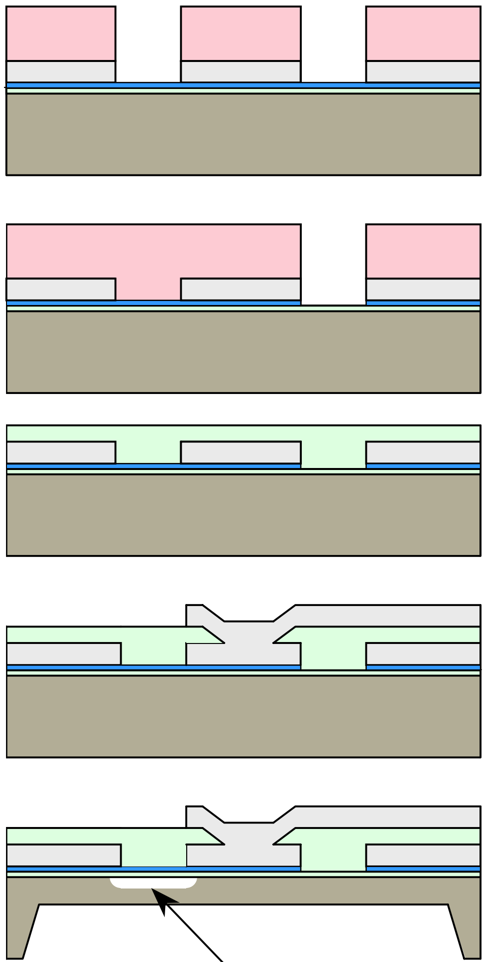
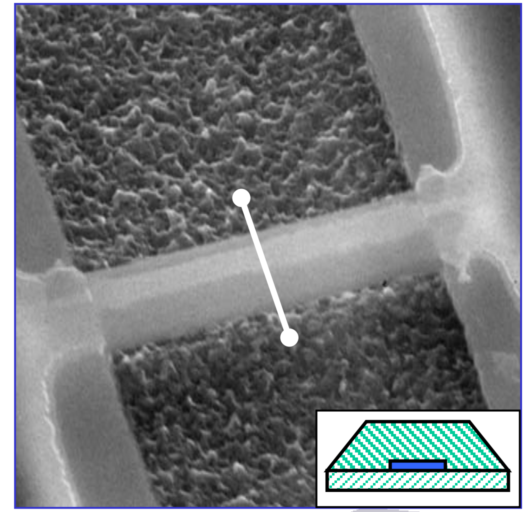
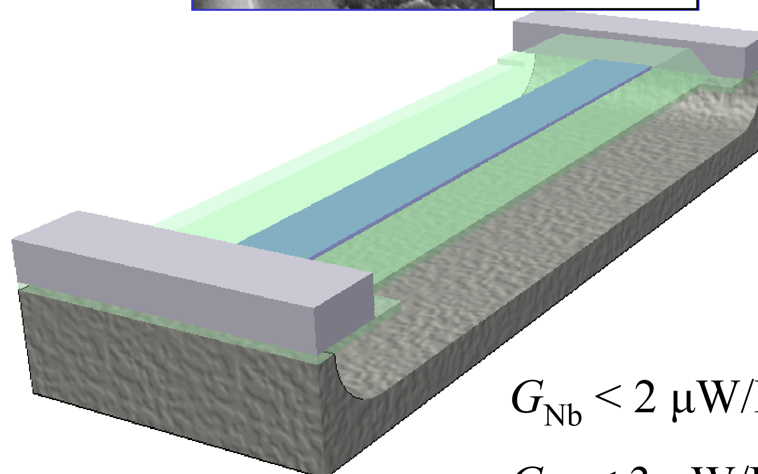
Air-Bridge Bolometers







Photoresist | Bolometer Metal
Aluminum | SiO_2 Insulator

$G_{Nb} < 2\ \mu W/K$

$G_{air} < 3\ \mu W/K$

$G_{ox} < 2\ \mu W/K$

Can the 2D Staring Array Approach be Scaled Up ?

• Present antenna-coupled bolometer arrays lack either pixel count, sensitivity, or speed

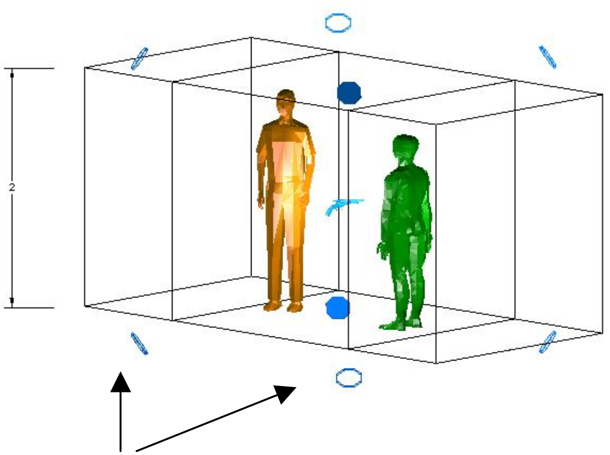
• Surface of the human body is ~ 3 m^2.

• At 1 cm resolution, ~ 30 kpixels needed : FPA real estate is a serious problem for scale up of staring arrays

• Scanning requires fewer pixels, but higher speed

• Higher frequency provides more pixels, but requires more sensitivity (to compensate for clothing penetration)

2 m cubic volume



8 FPA's at (111) directions

6 illuminators at (100) directions

8 x (60 x 60) FPA's,
35-54 degree antenna halfwidth
(7 – 11 dB directivity)

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Real Estate for Staring Arrays

- Mindless scale-up of an uncooled IR FPA doesn't work:
  - 25 μm pixels become 8 mm pixels (95 GHz)
    1.15 mm pixels (650 GHz)

  - So 20 kpixel (120 x 160) array is 1.2 m at 95 GHz, 18 cm
  - Poorly matched to density of CMOS readout circuits

- Consider compressing array:

Must match antenna beamwidth and optics speed
(smaller antennas have broader beams)

Optics requirements become very severe ($$) for large field-of-view

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Video imagery: observations

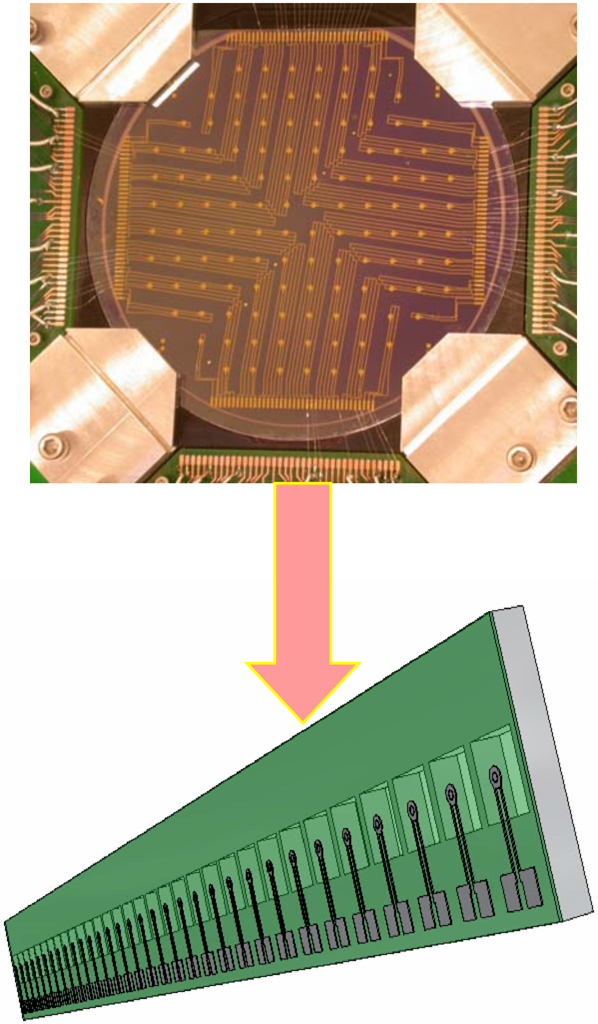
- Signal to noise ratio is clearly sufficient for detection
- Object recognition is challenging due to the small number of pixels & poor spatial resolution
- Strong specular reflections from objects at certain orientations
- Strong returns also from the skin
- *However, with larger pixel count & improved spatial resolution these issues can be tackled*

Imagery is clutter, not detector noise limited

1D Scanned System

The Quest for more pixels

- Instead of 2D array (12x12 pixels) use a linear array (1x128 pixels)
- Conical scanning optics, combined with a *linear* 128 pixel array (using the same readout)
- Yields 128x300 image pixels without sacrificing SNR
- Linear array pixels – greatly relaxed wiring requirements → improved coupling efficiency (~30 %)
- New IMPATT source, P_{peak}=10 W, P_{ave}=50 mW
- Overall, SNR improvement by a factor of ~600 expected!
- The sensitivity improvement helps especially in longer range applications



Active Systems favor Scanning Architectures

- If performance is sensitivity-limited, and
  - total illumination power
  - frame time
  - number of image pixels

  } fixed $N_{pix} = N_d \times N_{scan}$

  - duty cycle = pixel time/frame time = 1/Nscan

- Divide power among N_d detectors (illuminate only where scanning)

  Power per pixel $\propto N_d^{-1}$ Pixel time $\propto N_d$

  $$SNR \propto (\text{power per pixel}) \times (\text{pixel time})^{1/2} \propto N_d^{-1/2}$$

- <u>Optimum is fewer detectors, scanned faster, up to limits of scanner and detector speeds</u>

If noise is not white, scanning is even more favored

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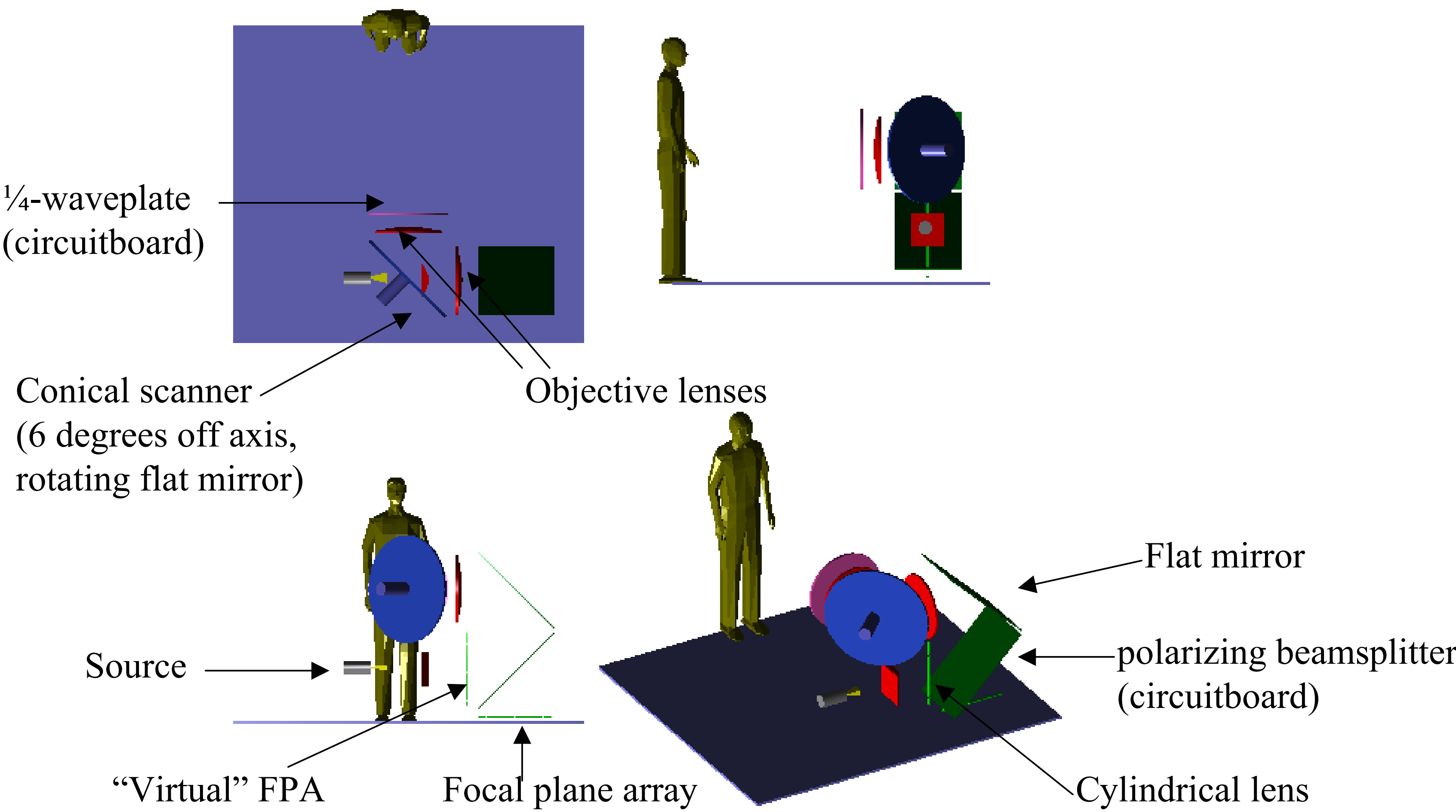
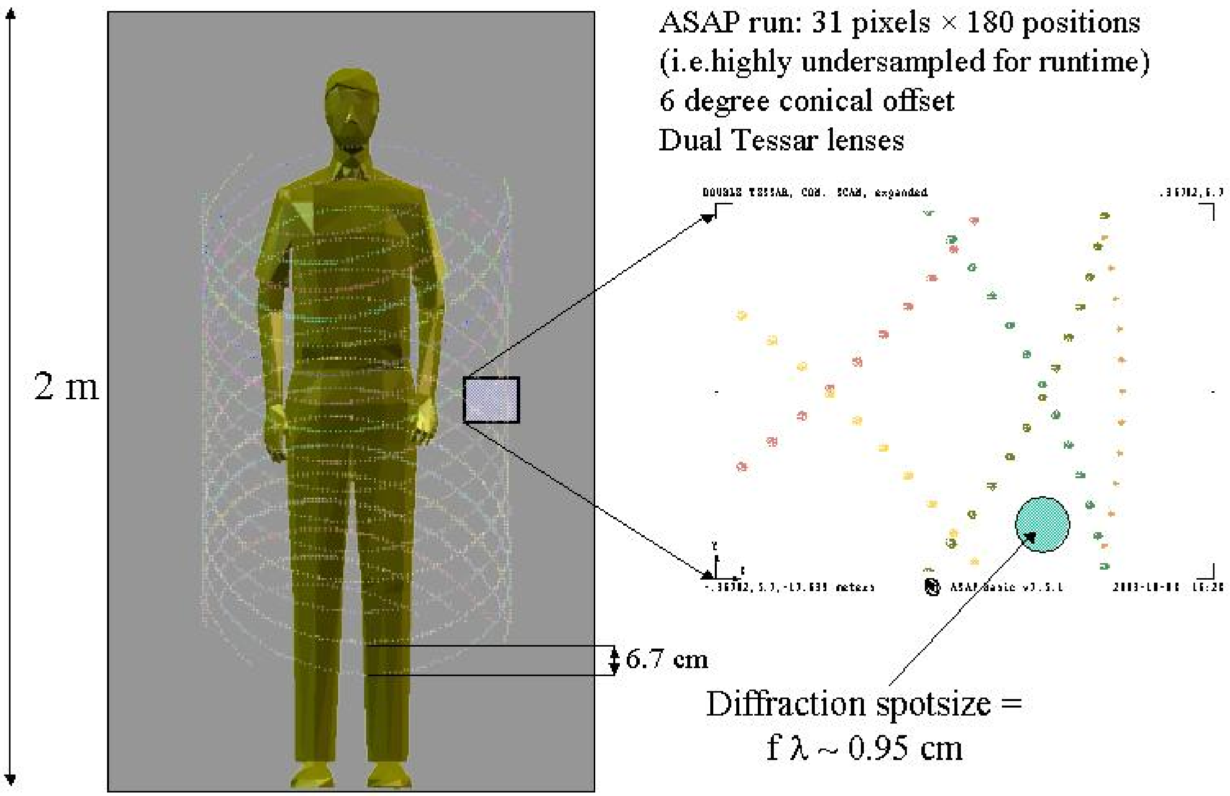
High Pixel-count, MM-wave Scanning System



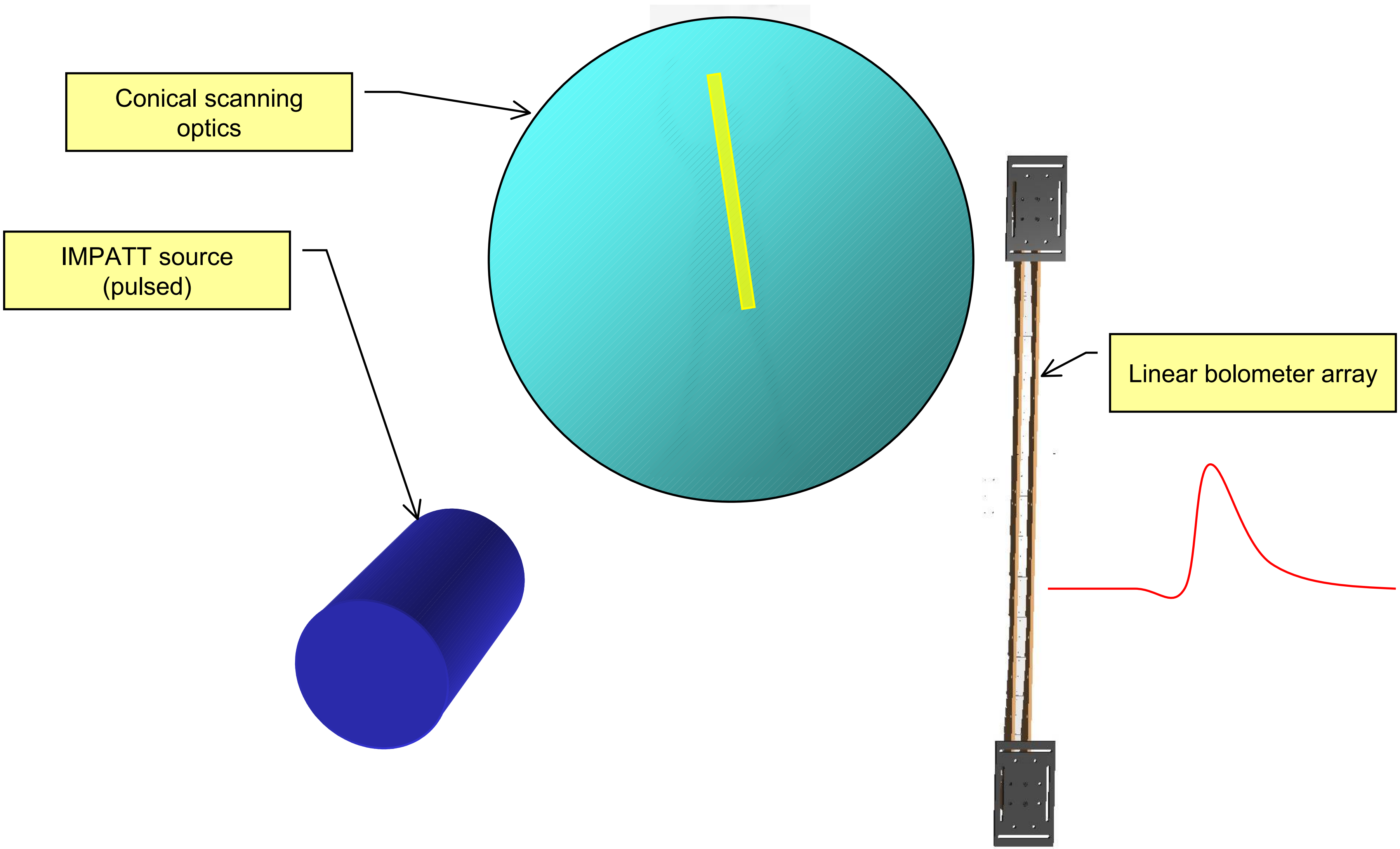
Conical Scan Sampling

- Pixel count
  - 128 detectors x
  - 300 scan angles
  - = 38.4 kpix
- redundancy

Conical Scan Coverage – To scale

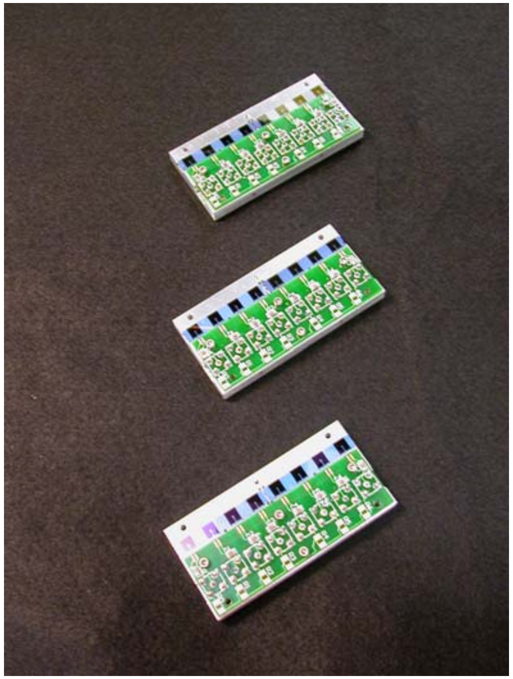
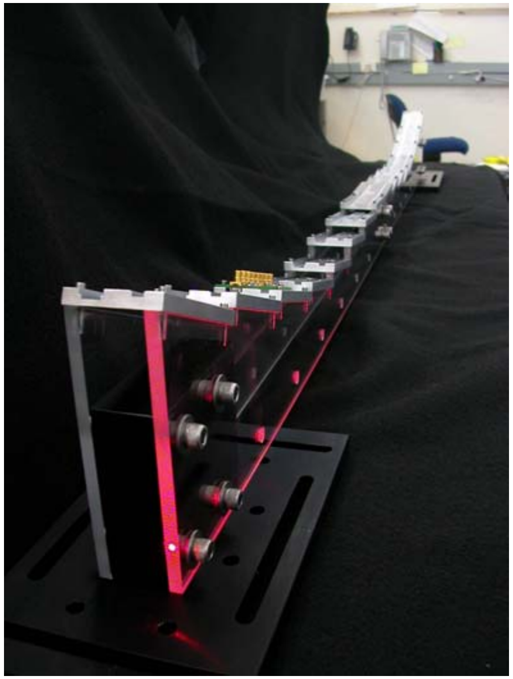


Linear array & Conical scanning



Linear array & Conical scanning

- The linear array consists of 16 modules with 8 pixels each
- Modules mount onto a “spine”
- Optics: aspheric doublet lenses (Polyethylene), D=48 cm, total loss = 1.3 dB at 95 GHz, diffraction-limited over +/- 35 degree FOV at f/3.1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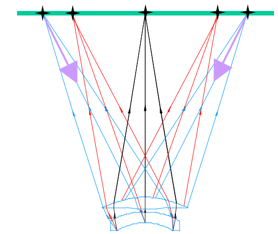
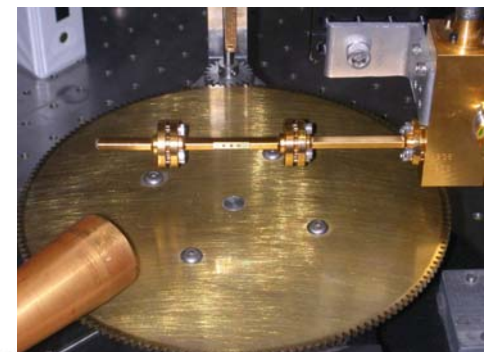
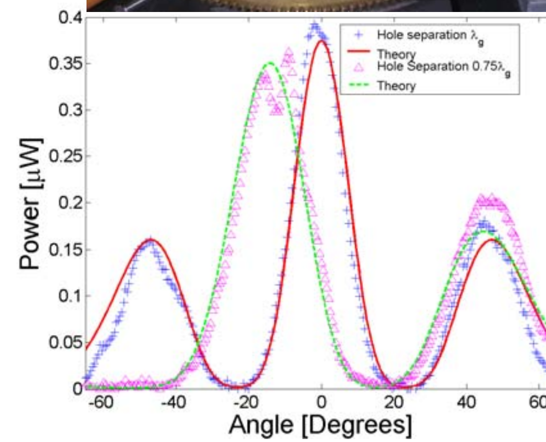
Line Source

- Desired source is an image of FPA
  - linear array of point sources, emitting into f/2.5 cones pointed toward exit aperture



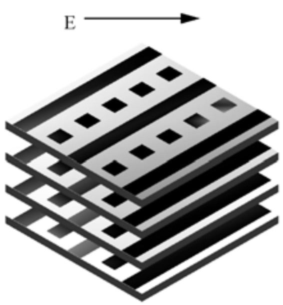


- At 95 GHz, implemented in waveguide
  - narrow wall holes emit as magnetic dipoles
- At 650 GHz, implement quasioptically with crossed cyclindrical lenslet array



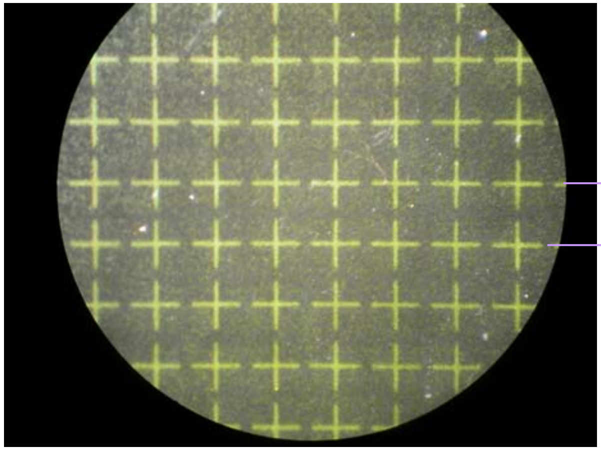
λ /4 plate and polarizer

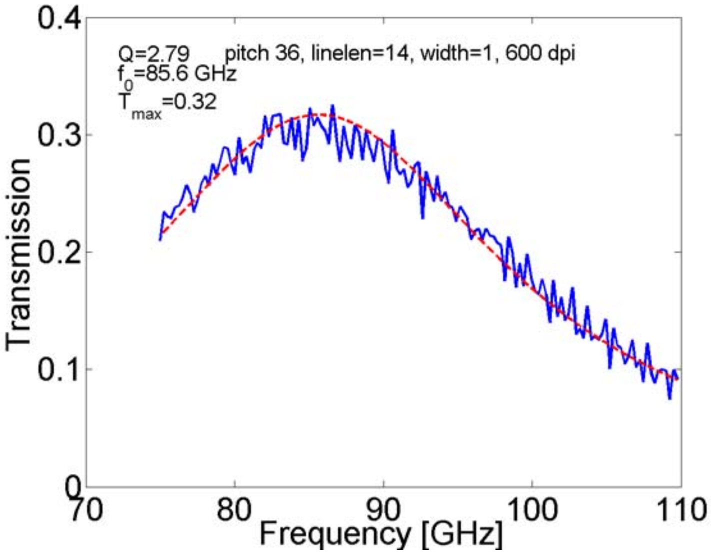
- Fabrication by laser printer, then metallic lamination
  - see Kondo, T. Nagashima, T. Hangyo, A. (2002), Conf. Digest for 27th Intl. Symp. IR and Mm Waves
  - large area (8 ½ x 11)
  - low cost
  - 100 μm linewidth well defined
  - high resistivity circumvented with electroplating



- "Waffle-grid" λ / 4 plate design
  - CU Boulder development
    - Leong and Shiroma, Elec. Lett. 38(22) (2002)
    - Shiroma and Popovic (Microwave and Guided Wave Lett. 6(5) (1996)

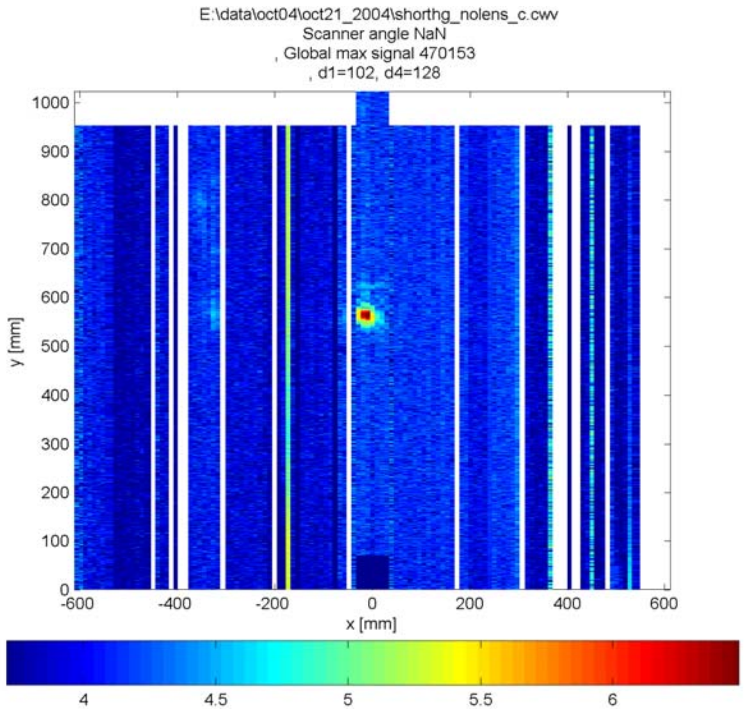
Laserprinted crossed-slot bandpass filter

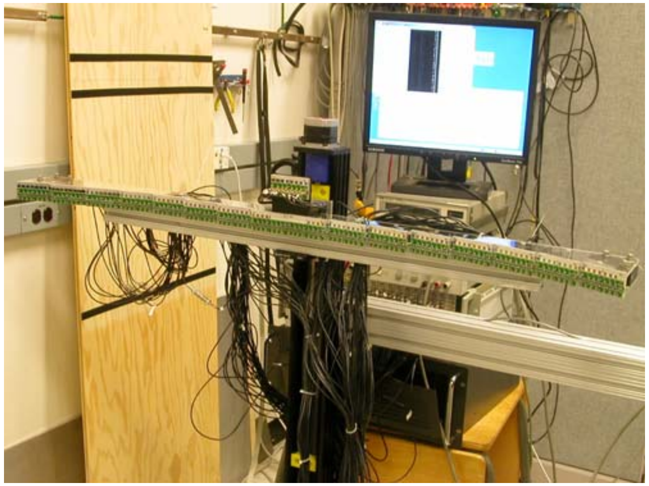


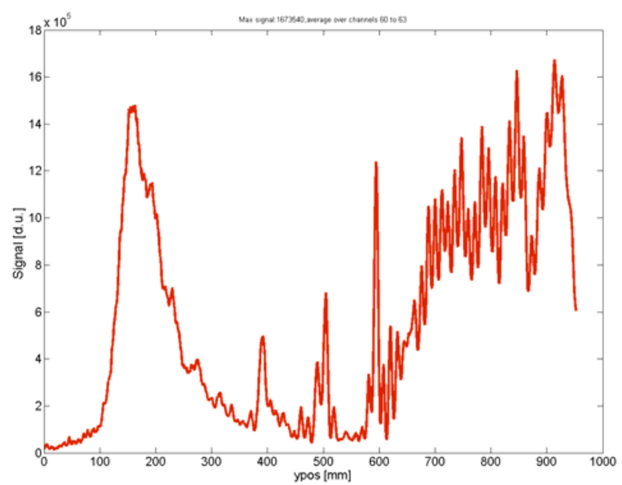


Linear array & Conical scanning

- System verification under way
  - Imaging of the source on the detector array to verify the illumination conditions & coupled power
- Issues found: interference of triplets







Migration to 650 GHz
TADD System Specifications

Specification	Value	Specification	Value
Frequency	655 GHz	Pixel count	128 � 300
Range	5 m	Illumination power	3 mW
Aperture Size	25 cm	Illumination efficiency	25 %
Field-of-view	2 � 4 m (h � w)	Detection efficiency	50%
Frame Rate	30 Hz	NEP	5 pW/Hz$^{1/2}$
Spatial resolution	1 cm	S/N ratio (one 30 Hz frame)	3

-

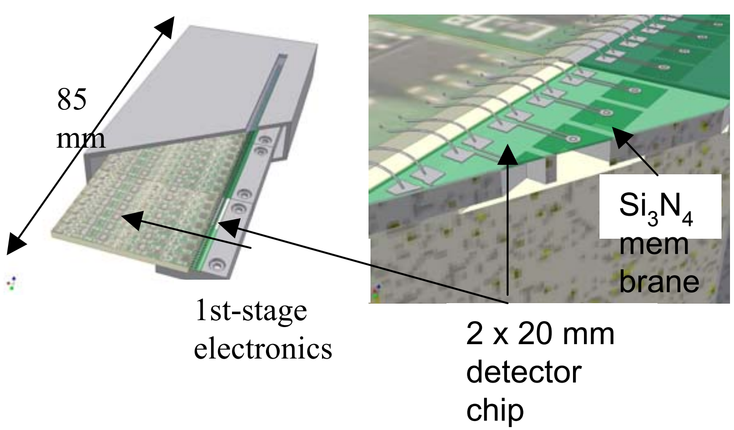
Table 1. Baseline TADD system specification and performance

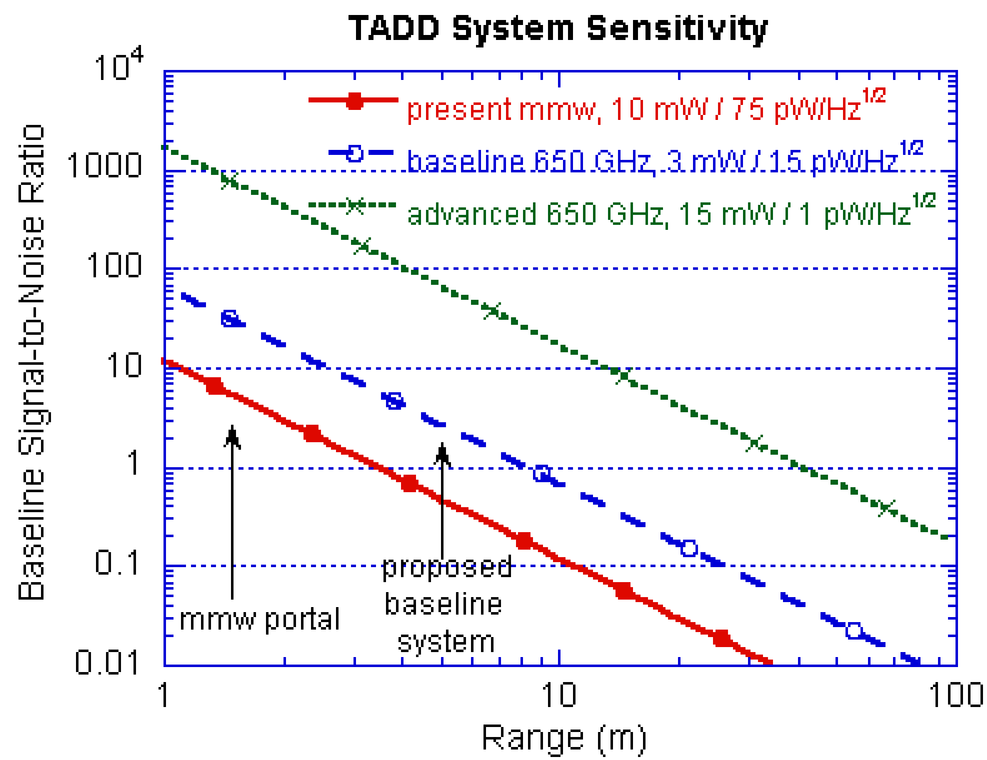
-

THz Active Direct Detection Sensitivity

• Source power and detector NEP control range

• R^{-2} dependence
not R^{-4} (conventional radar)
target in near field of aperture



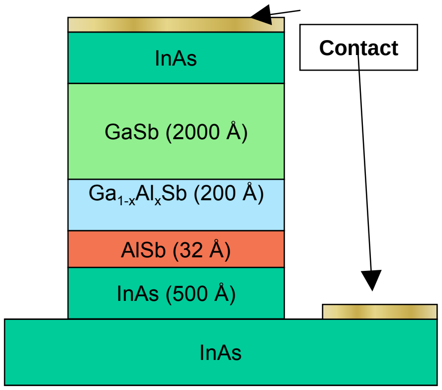


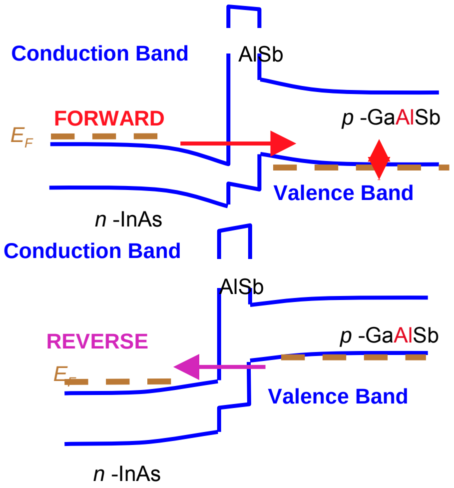
Sb-heterostructure quantum tunneling diodes

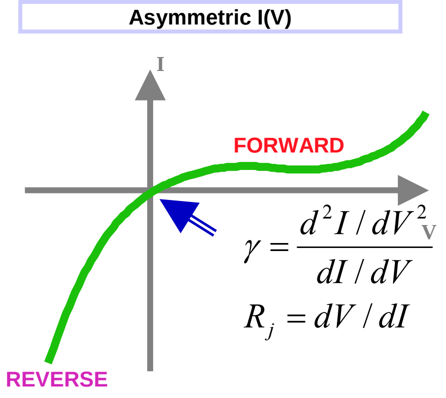
in collaboration with HRL Laboratories, Malibu, CA

Joel N. Schulman
Harris P. Moyer

- Diodes, unlike bolometers, do not suffer from phonon noise, but:
  - Schottky diodes (the most common diode detector) require a dc bias for sensitivity & impedance matching and suffer from huge 1/f noise
    - Detection is typically done *after* a RF amplifier
  - Their RF bandwidth is limited by the RC of the junction resistance & capacitance → small area required for high frequency operation
- **HRL Sb-heterostructure zero-bias diodes**
  - basic operation similar to the Esaki diode
  - Type II band gap alignment: n-InAs Conduction band minimum lies energetically below the valence band maximum in p-GaAlSb→ asymmetry in $I(V)$ characteristics.
  - Large nonlinearity at zero bias→ *no 1/f noise*
  - (2 μm)[2] diodes fabricated from epitaxial layers of InAs & GaAlSb using MBE







Sb-heterostructure quantum tunneling diodes: noise characterization

•Matched source, infinite load Responsivity:

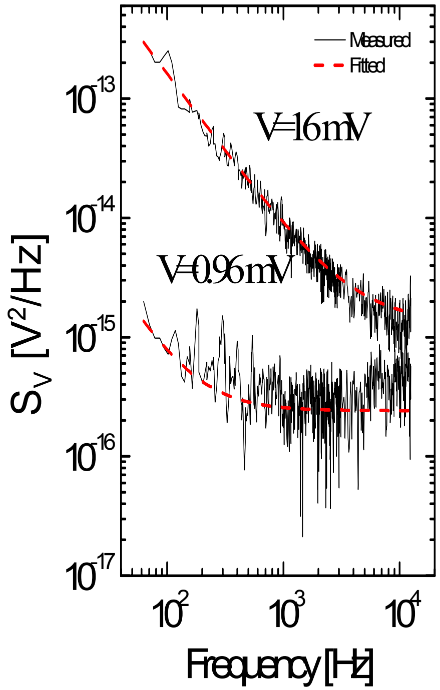
$$\Re_{v0} = \frac{R_j \gamma}{2} \frac{1}{\left\{(1 + R_s / R_j)\left[1 + R_s / R_j + R_s R_j C_j^2 \left(\Lambda\omega^2 / 4 + 3\omega_c^2\right) / 3\right]\right\}}$$

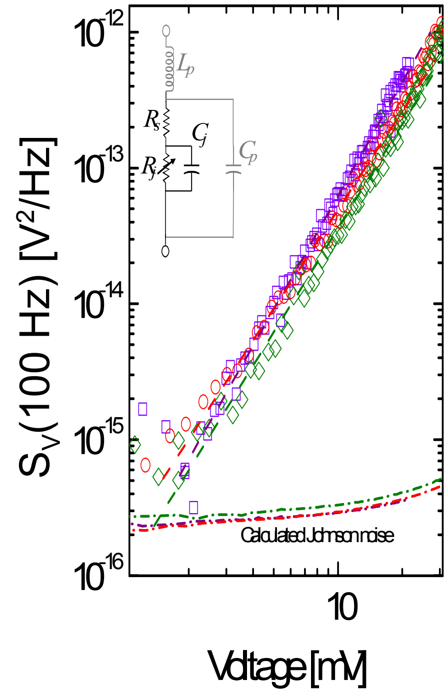
•NEP=*noise/responsivity*

•At V=0, $\omega_c/2\pi$=95 GHz

- •Best matched NEP~ 1 pW/Hz$^{1/2}$
- •Best unmatched NEP~ 4 pW/Hz$^{1/2}$ (Z_s=100Ω)

•Significant improvement over antenna-coupled microbolometers (10-25 pW/Hz$^{1/2}$)





$$S_V(f) = V_j^2 + V_{1/f}^2 + V_s^2,$$

$$V_j^2 = 4k_B T R_j(V)$$

$$V_{1/f}^2 = \alpha V^m f^{-r}$$

$$V_s^2 = 2eI\left(\frac{dV}{dI}\right)^2$$

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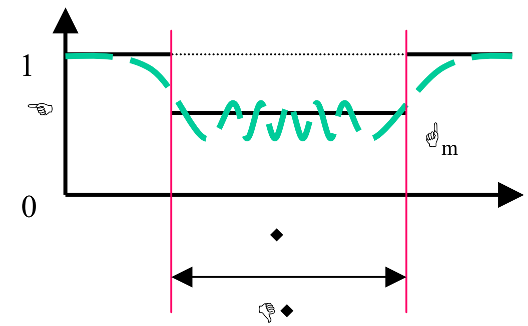
Colloquium, Sandia Natl. Lab, 11/17/04

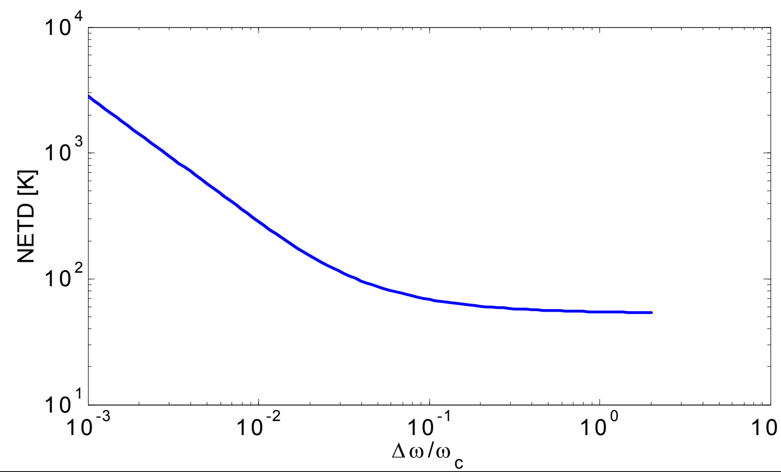
Matching considerations for passive direct detection

- Broader detector bandwidth – more signal power – more difficult impedance matching
- The Bode-Fano criterion gives the minimum average reflection coefficient ☝$_m$ for an arbitrary impedance matching network: $$\Gamma_m \geq e^{-\pi/\Delta\omega RC}$$
- Fraction of delivered power ♒=1-|☝$_m$|^2
- NETD is the true figure of merit for passive imaging of broadband (thermal) sources
- Enforcing the B-F criterion yields a best NETD~ 53 K for these non-optimized devices
- With further reduction in R_j, C_j, NETD~6 K is possible! sufficient for many imaging applications



$$NETD = \frac{NEP_m}{\eta \Delta f k_B \sqrt{2\tau_{int}}}$$

$$NETD = \frac{NEP_m(\Delta\omega)}{\left(1-e^{-1/\Delta f R_j C_j}\right)\Delta f k_B \sqrt{2\tau_{int}}} \approx \frac{NEP_m R_j C_j}{k_B \sqrt{2\tau_{int}}}, \Delta f \to \infty$$



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Active Imaging with ACMBs

- Fundamental trade-off: Cost & Complexity vs. sensitivity
- Antenna-coupled microbolometers are by far the simplest of the detector candidates
- What room temperature bolometers lack in sensitivity can be compensated with *the use of illumination: 5000 $ source → 5 mW average power (increase by 8 orders of magnitude!)*
- Program started in 2001 to develop a system demonstrator with pulsed noise sources & antenna-coupled microbolometers
- Moderate (120) pixel count to provide a system to study the phenomenology of active video rate mmw imaging

Conclusions

- For advanced checkpoint CWD, both mmw/THz and x-ray backscatter imaging offer penetration and resolution

- The relative advantages of mmw/THz and XRB depend on application details. Mmw/THz has advantages in
  - safety/privacy
  - throughput
  - cost

- An active mmw/THz imager based on bolometers
  - is simple and cheap
  - scales easily to THz frequencies
  - has enough sensitivity for CWD at ranges up to 5 m without any breakthroughs in component performance

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