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 breakthroughs, for large-format, real-time, low-cost THz imaging?
THz Imaging Arrays
Application Scenario

- 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 …

- Diffraction-limited resolution and good transmittance
  - $D = 1$ m (practical maximum) implies
    - $\text{res} > 2.5$ 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

Other 95 GHz measurements

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)

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 $\text{H}_2\text{O}$ 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
Technological Maturity, esp. Sources

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

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>Output power at 70 GHz (W)</th>
<th>Efficiency (%)</th>
<th>$P_{\text{out}} \cdot D^{1/2}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>1.4 W</td>
<td>17.5</td>
<td>1.4</td>
</tr>
<tr>
<td>10 %</td>
<td>2.0 W</td>
<td>25</td>
<td>0.63</td>
</tr>
<tr>
<td>4 %</td>
<td>2.7 W</td>
<td>33.8</td>
<td>0.54</td>
</tr>
<tr>
<td>2 %</td>
<td>3.1 W</td>
<td>38.8</td>
<td>0.44</td>
</tr>
</tbody>
</table>

~300 mW CW

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

Frequency (GHz)

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

Data courtesy T. Crowe, Virginia Diodes Inc.

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

Courtesy: Tom 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

• 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

  - To detect < 1 pW in 1/30 s with S/N=10, you need
    - either cryogenic detection ($NEP=3\times10^{-14}$)
    - or coherent detection ($T_{noise}=12,000$ K)
      - coherent detection is complex and expensive

  - $100$ GHz worth of indoor blackbody emission: 1.4 pW/K
  - $5000$ active source: 10 mW

- Active imaging should be easy, even with incoherent detection
What about Safety?

- FCC Ruling based on ANSI/IEEE standard C95.1-1992, for 100 GHz
  
  1.0 mW/cm² (general public)  5.0 mW/cm² (controlled access)

Occupational (controlled access) field strength limits

Not an issue for mmw or THz active imaging;
100 mW across 1 m² body area is x100 below guideline
THz Detection: technology matrix

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Sensitivity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent heterodyne</td>
<td>Good</td>
<td>Huge</td>
</tr>
<tr>
<td>Coherent direct (with preamplification)</td>
<td>Good</td>
<td>Large</td>
</tr>
<tr>
<td>Incoherent direct (no preamplification)</td>
<td>Moderate</td>
<td>Small</td>
</tr>
<tr>
<td>Antenna coupled microbolometers</td>
<td>Poor (active only)</td>
<td>Tiny</td>
</tr>
</tbody>
</table>

Maximum frequency

- ~200 GHz
- 600 GHz
- > 1THz
Figures of merit (Passive detection)

- For direct (incoherent) detectors, typically *Noise Equivalent Power (NEP)* [W/Hz\(^{1/2}\)]
- For coherent heterodyne typically expressed as *noise temperature*
- For passive detection of thermal (continuum) targets, *Noise Equivalent Temperature Difference (NETD)* is most useful (includes detection bandwidth)
- With active illumination, the most useful FOM is *Noise Equivalent Reflectance Difference (NERD)*
Antenna-coupled Microbolometers
Antenna-coupled microbolometers

• A thermally isolated, resistive termination for a lithographed antenna
• Signal coupled to the bolometer changes its temperature: $\Delta T = \frac{P_{inc}}{G}$
• A DC current is used to sense the resistance of the bolometer, given by $R = R_0(1 + \alpha \Delta T) = R_0(1 + \beta I^2)$
• 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

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

Earlier work on ACMBs
Tong 1983
Rebeiz 1990
Hu 1996
Microbolometer Sensitivity Limits

- For passive imaging, ACMB’s lack the necessary sensitivity

How the calculation works:

\[ P_{\text{min}} = \frac{\text{NEP}}{\sqrt{2\tau}} \]

\[ \text{NEP} = \sqrt{4kT^2G} \]

\[ G = G_{\text{dev}} + G_{\text{air}} + G_{\text{rad}} \]

\[ G_{\text{air}} = (0.025 \text{ W/m-K})A/L \]

\[ G_{\text{rad}} = \frac{dP}{dT} \text{ where} \]

\[ P=\sigma T^4A \text{ or } \pi^2k^2T^2/6h \]

(multimode or single-mode)

For current IR,

\[ A=50 \times 50 \mu m, \]

\[ L = 2.5 \mu m \text{ (current)} \text{ or } 50 \mu m \text{ (high aspect)} \]

For NIST microbridge,

\[ A=2 \times 10 \mu m, \]

\[ L = 2 \mu m \]
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 = $\lambda_{guide}$
- Electrically thin substrate $h < \lambda_{dielectric}/20 = 50\mu m$

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

0.86 mm

1 µm

10 µm
FPA fabrication

- Simple fabrication: only Nb, Au (or Al), SiO₂
- 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 SiO₂ for crossovers
Define vias through the SiO₂, 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 $\beta$ [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

\[ V(I) = IR_0 (1 + \beta I^2) \]
Passivated bolometer properties

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

![Graph: Single chip, exposed bolometers](image1)

![Graph: Micromachined Array, Passivated Bolometers](image2)
Scanned Imaging System

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

Erich Grossman, grossman@boulder.nist.gov
Colloquium, Sandia Natl. Lab, 11/17/04
Gun Images (rev. 2 optics)

Conclusion #1: Unpredictable hotspots
Gun Rotation Movie
Compare Illumination Modes

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

• Some objects show surprising features:

   ![Top View](Image)

   Non-specular peaks are not rotationally symmetric, but have $k$ displaced toward edge

   ![Specular peaks](Image)

   Metallic Knife

   Ceramic Knife
# Active THz Imaging Arrays
## Program Directions, Milestones

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

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

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

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

- This speed can be traded for pixel count via scanning

Prior mmw ACMB arrays
- Tong (1983)
- Rebeiz (1990)
- Hu (1996)
and many others
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%

Responsivity-Resistance Scatterplot

Responsivity1/2 (A⁻¹)
Resistance (ohms)
Active Imaging System Block Diagram

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

=Anomalous polarization response
=High coupling efficiency
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 SiO₂, Released with XeF₂ etch Of underlying Si
Air-Bridge $dv/di$ vs. $T$

- **Al antenna metal**
- Maximum $I_{bias} \approx 1.7$ mA
- $G = 4.5$ $\mu$W/K
- Johnson-noise limited
- $\tau \approx 4$ $\mu$s
- $TCR = 0.13$ % per degree K
- $\beta = 54$ V/(W·mA)
- Responsivity = 86 V/W

Differential Resistance vs. Substrate Temperature
Air-Bridge Bolometers

$G_{Nb} < 2 \ \mu W/K$
$G_{air} < 3 \ \mu W/K$
$G_{ox} < 2 \ \mu W/K$

Pattern Antenna
Pattern Bolometer
Deposit Insulator
Pattern Wiring
Substrate Etch

Air Gap

Photoresist  Bolometer Metal  SiO$_2$ Insulator
Aluminum

Erich Grossman, grossman@boulder.nist.gov
Colloquium, Sandia Natl. Lab, 11/17/04
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 \( \sim 3 \text{ m}^2 \).

• At 1 cm resolution, \( \sim 30 \text{ kpixels needed} \): 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)

\[
8 \times (60 \times 60) \text{ FPA’s,} \\
35-54 \text{ degree antenna halfwidth} \\
(7 – 11 \text{ dB directivity})
\]
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
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, $P_{\text{peak}}=10 \, \text{W}$, $P_{\text{ave}}=50 \, \text{mW}$
- 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 \( N_{\text{pix}} = N_d \times N_{\text{scan}} \)

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

- Divide power among \( N_d \) detectors (illuminate only where scanning)
  
  \[
  \text{Power per pixel} \propto N_d^{-1} \\
  \text{Pixel time} \propto N_d \\
  \text{SNR} \propto (\text{power per pixel}) \times (\text{pixel time})^{1/2} \propto N_d^{-1/2}
  \]

- **Optimum is fewer detectors, scanned faster, up to limits of scanner and detector speeds**

  If noise is not white, scanning is even more favored
High Pixel-count, MM-wave Scanning System

- Quarter-waveplate (circuitboard)
- Conical scanner (6 degrees off axis, rotating flat mirror)
- Objective lenses
- Source
- "Virtual" FPA
- Focal plane array
- Flat mirror
- Polarizing beamsplitter (circuitboard)
- Cylindrical lens
Conical Scan Sampling

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

- redundancy

Conical Scan Coverage – To scale

ASAP run: 31 pixels x 180 positions
(i.e. highly undersampled for runtime)
6 degree conical offset
Dual Tessar lenses

Diffraction spotsize =
\[ f \lambda \sim 0.95 \text{ cm} \]
Linear array & Conical scanning

Conical scanning optics

IMPATT source (pulsed)

Linear bolometer array
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
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 cylindrical 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
    - Shiroma and Popovic (Microwave and Guided Wave Lett. 6(5) (1996)
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

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

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

![Graph showing TADD System Sensitivity]

- Present mmw: $10 \text{ mW} / 75 \text{ pWHz}^{1/2}$
- Baseline 650 GHz: $3 \text{ mW} / 15 \text{ pWHz}^{1/2}$
- Advanced 650 GHz: $15 \text{ mW} / 1 \text{ pWHz}^{1/2}$

![Diagram showing mmw portal and proposed baseline system]
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:

\[ R_{\nu 0} = \frac{R_i \gamma}{2} \left[ \frac{1}{1 + R_i / R_j} \right] \frac{1}{1 + R_i / R_j + R_i R_j C_j^2 \left( \Lambda \omega^2 / 4 + 3 \omega^2 \right) / 3} \]

• 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\(^{1/2}\) (\( Z_s = 100\Omega \))

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

\[
S_v (f) = V_j^2 + V_{1/f}^2 + V_s^2,
\]

\[
V_j^2 = 4k_B T R_j(V)
\]

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

\[
V_s^2 = 2eI \left( \frac{dV}{dl} \right)^2
\]
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 $\phi_m$ for an arbitrary impedance matching network:
  $$\Gamma_m \geq e^{-\pi / \Delta \omega RC}$$

- Fraction of delivered power $\approx 1 - |\phi_m|^2$
- 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
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 $\rightarrow$ 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.