Real-time THz Imaging Using Quantum-cascade Lasers and Focal-plane Array Cameras

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Unique features of sensing and imaging at THz frequencies:

— Distinctive spectral “fingerprints” of big molecules,
— can see through optically opaque materials.
Terahertz “fingerprints” of several explosives

![Terahertz spectra of explosives](image)

Different explosives have unique terahertz spectral fingerprints

Kemp et al. 2003, Proc SPIE 5070
TNT “phonon” mode at 3.48-THz (116 cm$^{-1}$)

Courtesy X. C. Zhang at RPI.
T-rays imaging for drug detection
(K. Kawase, OPN, October 2004)

Three different drugs, MDMA (left), aspirin (center), and methamphetamine (right), have different images in T-rays.

Pictures taken with a THz OPO (1.3-2 THz) and mechanical scans.

Figure 1. (a) Schematic of THz spectroscopic imaging system using THz wave parametric oscillator. (b) View of the samples. The small polyethylene bags contain (left to right): MDMA, aspirin and methamphetamine. The bags were placed inside the envelope and the area indicated by the yellow line was scanned.

Figure 2. (a) Multispectral image of the target, recorded at seven frequencies between 1.32 and 1.98 THz. (b) Spatial patterns of MDMA (yellow), aspirin (blue) and methamphetamine (red) extracted from the multispectral image by use of fingerprint spectra.
Desired T-rays imaging systems

• **Sources:**
  — Compact and solid-state with >10 mW output;
  — portable ⇒ operating above thermoelectric cooler temperatures;
  — multicolor, covering a broad frequency range (1-10 THz);
  — frequency tunable;
  — phase-locked with narrow linewidth (for sharp spectral fingerprint detection).

• **Detectors:**
  — Focal-plane arrays at video rate (30 frames/sec.) for real-time imaging and screening.
Real-time THz imaging set-up

Microbolometer-array cameras

\[ T_{bolo} = T_o + \frac{P}{G} \left( 1 - e^{-\frac{t}{\tau}} \right) \]

\[ \tau = \frac{C}{G} \approx 13 \text{ ms} \]

- Broadband
- video rate (60 fr/s)
Differential Scheme for Real-time Imaging

Frame Acquisition Sequence:

- Most sensitive to 7 – 14 μm wavelengths for night vision, overpowers THz signals.
- Differential scheme removes strong infrared background and reduce $1/f$ noise.
Real-time THz Videos

Plastic Mechanical Pencil

- 4.3 THz (68 um)
- 48 mW peak power
- Using f/1 -- 25 mm Si Lens
- 320x240 pixel VOx microbolometer camera
- SNR ~ 200
- Images shown in log scale (light color represents high intensity)
Real-time THz Videos

Metal Cutouts in Paper Envelope
Real-time THz Videos

Dried Leaf
Real-time THz Videos
Polystyrene block with an embedded metal screw
Real-time THz Videos

Pencil hand writing inside a paper envelope
Real-time THz imaging over stand-off range (>25 m)

(Alan Lee et al. to be published in APL (2006))

~23 meters from the source
Transmissive image over stand-off range (>25 m)

(Alan Lee et al. to be published in APL (2006))
Future developments

• Improve signal/noise ratio for real-time imaging in reflective mode. Steps include:
  — develop microbolometers specifically designed to operate at THz frequencies,
  — develop cryogenic focal-plane cameras, for example THz QWIPs,
  — increase the power levels of THz QCLs.

• Increase the long-range capability by going to longer wavelengths. For example, at ~1.5 THz (200 µm wavelength) $\alpha \sim 0.23$ dB/m compared to ~0.6 dB/m at ~4.9 THz. $\alpha$ is even lower at sub-THz frequencies, ~0.1 dB/m at ~0.9 THz.

• Using multicolor sources to pick out spectral “fingerprints”.
Sensitivity: Microbolometer Absorption

- Electrical NEP (~$1 \times 10^{-12}$ W/√Hz) is reduced by:
  - 4% absorption at 4.3 THz
  - 38% transmission through Ge camera window
  - Differential only allows pixels to reach 42% of maximum temperature

Results in calculated optical NEP of 200 pW/√Hz
Measured sensitivity

• Noise $\sigma = 2.56 \text{ counts}/\sqrt{\text{Hz}}$

• Optical NEP = $\sigma/R = 320 \text{ pW}/\sqrt{\text{Hz}}$ @ 4.3 THz, more than two orders of magnitude worse than electrical NEP

• With 48 mW SNR = 340 (average over focal plane)
Most important issue for long-range imaging

It is frequency, frequency, and frequency!

Because of exponential attenuation in space, $P = P_0 e^{-\alpha L}$, range only increases logarithmically with power.
Atmospheric Transmission

- Absorption due to water vapor

Diagram showing frequency [THz] vs. Loss [dB/m] with peaks at approximately 1.5 THz and 4.9 THz.
Transmission of different materials at THz
(J. C. Dickinson et al., UMass Lowell (2006))

Materials are more transparent at longer wavelengths.
1.56-THz imaging in reflective mode
(J. C. Dickinson et al., UMass Lowell (2006))

Image taken using a FIR gas laser and a Schottky-diode mixer.
A recently developed high-power QCL at ~4.4 THz

198 µm × 1.21 mm ridge
98 µm × 2.15 mm ridge

- $P_{\text{max}} \approx 248 \text{ mW}$ (pulsed) and 138 mW (CW).
- Using a narrower ridge (~98 µm), ~50 mW of power at pulsed-tube cooler temperature (~30 K), T-rays movies possible.
High-power metal-metal waveguide lasers with good beam patterns

QC Laser mounted in PT Cryorefrigerator

Si Hyperemisphere

Off-axis Paraboloid

3 mm Aperture

10 cm

20 cm

Off-axis Paraboloid

50 mW

7 mW

30 mW

Microbolometer Camera

240x320 pixel

Ge Window

VOx Bolometer Element