Stand-off Detection of Trace Explosives by Infrared Photothermal Imaging

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Trace Contamination

- For manufacture there are Mil Spec explosives particulate sizes
- Munitions or IED surfaces are contaminated with trace particulate explosives.
- Fingerprints from C4 particles generate particle size range
  - @ 20 micron original size of particle
  - @ 4 µgrams in 1st print
  - @ 0.4 µgrams in 10th print

Understand the source
### Explosives & Spectral Characteristics

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNT</td>
<td>C-NO$_2$</td>
</tr>
<tr>
<td>RDX</td>
<td>C-N-NO$_2$</td>
</tr>
<tr>
<td>HMX</td>
<td>C-N-NO$_2$</td>
</tr>
<tr>
<td>TETRYL</td>
<td>C-N-NO$_2$</td>
</tr>
<tr>
<td>PETN</td>
<td>C-O-NO$_2$</td>
</tr>
<tr>
<td>NG</td>
<td>C-NO$_2$</td>
</tr>
<tr>
<td>EGDN</td>
<td>C-O-NO$_2$</td>
</tr>
<tr>
<td>Am. Nitrate</td>
<td>NH$_4$NO$_3$</td>
</tr>
<tr>
<td>Urea Nitrate</td>
<td>CH$_5$N$_2$O, NO$_3$</td>
</tr>
</tbody>
</table>

- Example Infrared Absorption Bands:
  - Covalent nitrate: 6.1-6.6 μm
  - Ionic nitrate: 7.0-7.5 μm

#### 6.25 microns targets the common explosives
(Common materials have low absorption in this region)

- Low transmission at absorption bands
- Several absorption bands are common to these explosive materials
- 6.25 μm targets common explosives
  - N-O asymmetric stretch
  - Common materials exhibit low absorption in this region
- Fortuitous transmission window at 6.25 μm
  - Offers stand-off interrogation

Remote Explosive Detector (RED) Concept

- IR lasers can be used to resonantly couple energy to explosives, drugs, or other chemicals
- Eye-safe, stealth detection
- Thermal radiation can be collected and analyzed at stand-off distances

Quantum Cascade Laser

- Microfabricated laser
  - foundry fabrication in quantity → inexpensive devices
  - Compact IR source
- Single wavelength output
  - targets specific functional groups
- Room temperature operation
- Up to 1 Watt CW output
- Commercially available
  - We buy C-mounted QCL from AdTech Optics
  - We buy turn-key QCL from Daylight Solutions, Inc.

Quantum Cascade Laser (QCL)

- 2 cm
- 6.25 µm
**NRL (FLIR) Thermal Imager**

- **FLIR (Indigo) Photon Block II**
  - Un-cooled bolometer array
  - 320 X 240 pixels (38 µm)
  - Analog and digital output
  - B&W or false color images
  - Movies here with 50 mm IR lens
  - NETD (noise equivalent temperature) @85 mK
  - Filter limits coverage to 7-12 microns (2-12 nominal)
  - “OEM” platform – already fielded for applications
  - Small, light, relatively low power
  - 30 frames/sec (33 mS between frames)
  - Intrinsically limited response time (slow cooling)

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**Remote Explosives Detection (RED) Testbed**

- Dedicated Testbed
- 4’ X 8’ table
- Co-aligned lasers
- Co-linear incident and detection paths
- Digital software interface array readout
- Environmental chamber (not shown in photo)
**Differential Imaging**

1. Pulse or chop laser at video frame rate
2. Compare “Laser On” vs. “Laser Off” frames
3. Overlay differential with visible image

Could repeat with on/off resonance or other laser wavelengths to increase sensitivity and selectivity.

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**Analyte Selectivity for Dual Analyte Sample (RDX & TNT)**

Sample illuminated by a heatgun: no laser

Differential images of QCL-heated samples:

- **ν₁ = 1635 cm⁻¹**: Off-resonance
- **ν₂ = 1618 cm⁻¹**: TNT resonance
- **ν₃ = 1600 cm⁻¹**: RDX & TNT
- **ν₄ = 1585 cm⁻¹**: RDX resonance

NOTE: Red circles indicate the laser spot size.
**Standoff Detection of TNT**

- 1 meter standoff (not limited to this distance)
- 20 mW, $\lambda$=6.25 micron, 10 mm diameter QCL beam
- $\Delta T$ is $\sim$ 1 °C for bright grain seen in both images.
- Individual particles @ 10-100 microns (0.8 – 800 ng)

![TNT grains in thermal and laser differential images](image)


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**Cart-based System Design**

For Field Testing

- “Cart-mounted” components:
  1. QCL module (4 lasers)
  2. Collection optics (lenses and mirrors)
  3. Steering gimbal
  4. Co-focused:
     - IR detector
     - visible camera
  5. Computer based:
     - System control software
     - Signal processing/alarm algorithm

![Cart-mounted system diagram](image)
Optical Layout

- Modular design
- Co-aligned:
  - QCL excitation
  - IR detection
  - Visible alignment
- 12 mm collimated beam for long standoff
- IR and visible imaging systems are co-focused
- Approved eye-safe for use around people by Navy Laser Safety Review Board

QCL Module Layout

**RED QCL Module**
- 5.2 µm (~30 mW) “off resonance 1”
- 6.25 µm (~30 mW) “on resonance 1”
- 7.41 µm (~30 mW) “on resonance 2”
- 658 nm –alignment laser (~ 1 mW)
- Co-linear, 12 mm collimated
- Pick-off beam for output power normalization
- Operate independent of temperature
RED Cart Software Interface

- Written in-house for this specific application
- Microsoft Visual Studio C Sharp
- Synchronizes experiment
- Monitors output
- Graphic display
- Analyzes data

Experimental Sequence and Signal Processing
1. Control/synchronize QCL pulsing sequence
2. Correlate detector signal with output $\lambda$
3. Turn a series of signals into a differential
4. Then into an on/off resonance comparison
5. Three wavelengths for enhanced selectivity
6. Process into an alarm signal

ALARM!

Signal 1 | Signal 2 | Signal 3 | Signal 4

Pulse Visible | Pulse 7.4 QCL | Pulse 6.2 QCL | Pulse 5.2 QCL

< 1 second of time in total
Field Testing at Yuma Proving Ground

- Effects of temperature, sunlight, humidity, dust
- TNT, RDX, PETN, C4, Tetryl, Comp B, PBX4, PE4
- Best data at 10 meter
- Data out to 30 meter
  - difficult to stabilize optics
- Camera and single channel
- Very challenging environment
  - For electronics, optics, people

Sample: RDX
Stand-off distance: 10m
T<sub>amb.</sub> = 22 °C
RH = 13%
V<sub>wind</sub> = 10 mph

IR image

Differential images

- λ = 0.65µm (off res.)
  - Δ = -0.04 counts
- λ = 7.4µm (on res.)
  - Δ = 1.28 counts
- λ = 6.3µm (on res.)
  - Δ = 1.02 counts
- λ = 5.2µm (off res.)
  - Δ = -0.09 counts

RDX detected at 10 meter stand-off
Conclusions

- **Eye-safe** IR lasers have been utilized to selectively heat trace amounts of explosives to for photothermal imaging analysis.
- In photothermal detection applications (RED) a miniature IR quantum cascade laser (QCL) and thermal imaging detector have been used to detect and map trace explosives in a stand-off configuration.
- RED concept has been demonstrated on variety of substrates, analytes, in/out doors, and at significant standoff distances.
- Sponsored by OSD/RRTO and NRL
Air Infrared Transmission

- The fortuitous air window for explosives between 6 and 6.5 microns is away from night vision and missile heat seeking wavelengths
- We need to detect in LWIR because explosives are not “black bodies”
- Kirchhoff’s Law – their emissivity matches their absorptivity

NRL/AdTech Optics QCL

- OEM/COTS c-mounted QCL from AdTech Optics
- Operates at room temperature and slightly above
- Temperature controlled for constant output \( \lambda \) and power
- >180 mW Continuous Wave (higher in pulsed mode)
**Interferent/“confusant” Testing**

- Broadband absorbers will heat independent of wavelength.
- Distinguish this “confusant” by difference of differences
- 1325 counts/19.5mW = 67.9 (\(\lambda = 1600 \text{ cm}^{-1}\))
- 766 counts/11mW = 69.6 (\(\lambda = 1625 \text{ cm}^{-1}\))
- “Difference” 67.9 – 69.6 ~ zero (not an “analyte of interest”)

**Differential images of carbon black sample on a gold mirror**

When scaled by input power, the difference between the images is @ = zero.

Therefore the sample is not an “analyte of interest”.

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