Stand-off Detection of Trace Explosives by Infrared Photothermal Imaging

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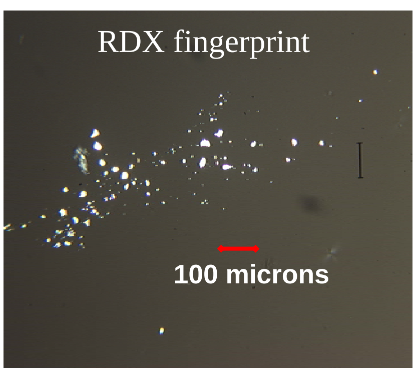
Trace Contamination



NIST (J. Verkouteren)
Journal of Forensic Sciences 52 (2), 335–340

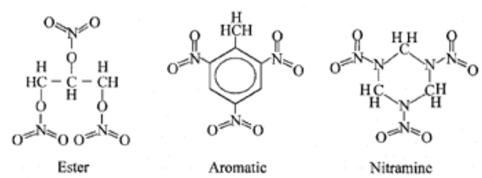
Understand the source

- 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

Explosives & Spectral Characteristics

Explosive	Functionality
TNT	$C\text{-}NO_2$
RDX	$C\text{-}N\text{-}NO_2$
HMX	$C\text{-}N\text{-}NO_2$
TETRYL	$C\text{-}N\text{-}NO_2$
PETN	$C\text{-}O\text{-}NO_2$
NG	$C\text{-}NO_2$
EGDN	$C\text{-}O\text{-}NO_2$
Am. Nitrate	NH_4NO_3
Urea Nitrate	CH_5N_2O, NO_3

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

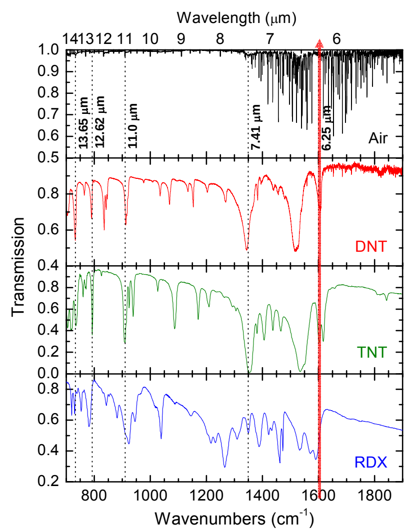


6.25 microns targets the common explosives

(Common materials have low absorption in this region)

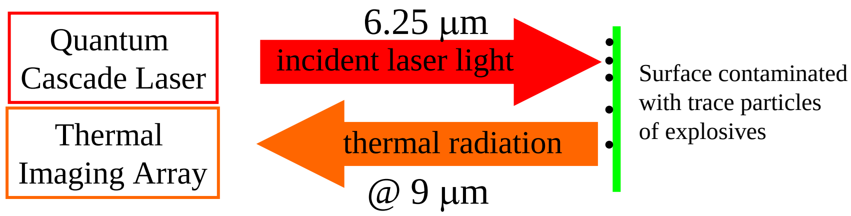
Infrared Spectra of TNT, DNT & RDX

- 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



R. Furstenberg *et. al*, Applied Physics Letters, **93**, 224103 (2008)

Remote Explosive Detector (RED) Concept



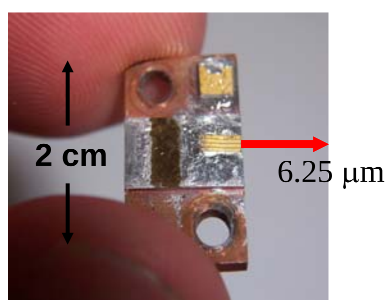
U. S. Patent Application 12/255,103
International Patent # WO2009055370

- 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

IR photon source

- 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.



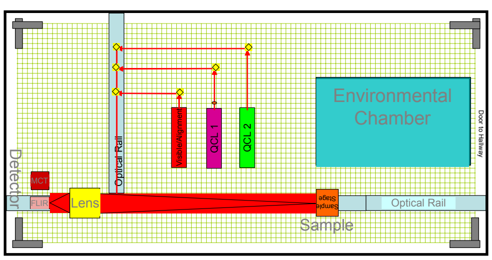
Quantum Cascade Laser (QCL)

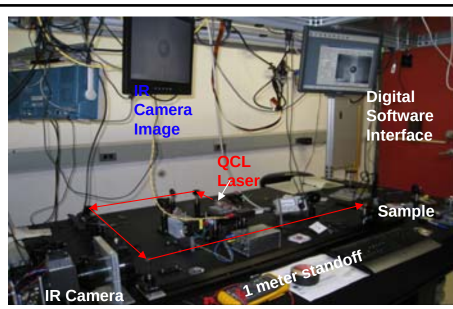
QCL device from M. Razeghi
Northwestern University
Center for Quantum Devices

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)

Remote Explosives Detection (RED) Testbed



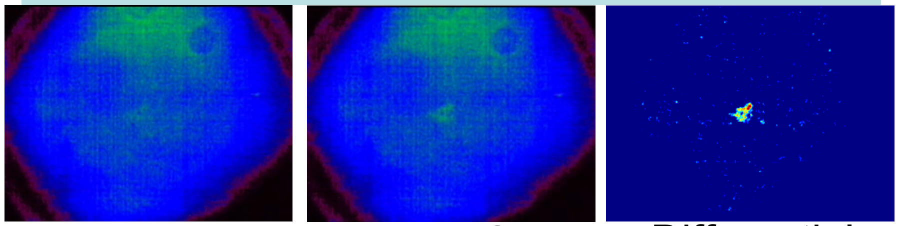


- Dedicated Testbed
- 4’ X 8’ table
- Co-aligned lasers
- Co-linear incident and detection paths
- Digital software interface array readout
- Environmental chamber (not shown in photo)

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

Thermal images of RDX on gold mirror illuminated with chopped QCL IR beam



Laser Off | Laser On | Differential

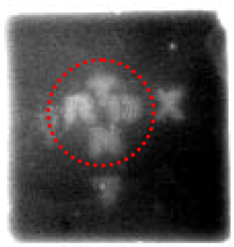
Could repeat with on/off resonance or other laser wavelengths to increase _sensitivity_ and _selectivity_.

Analyte Selectivity for Dual Analyte Sample

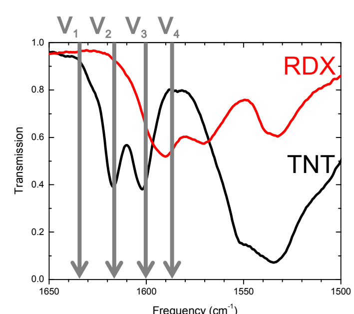
(RDX & TNT)

Sample illuminated by a heatgun: no laser

Furstenberg et. al, APL, **93**, 224103 (2008)

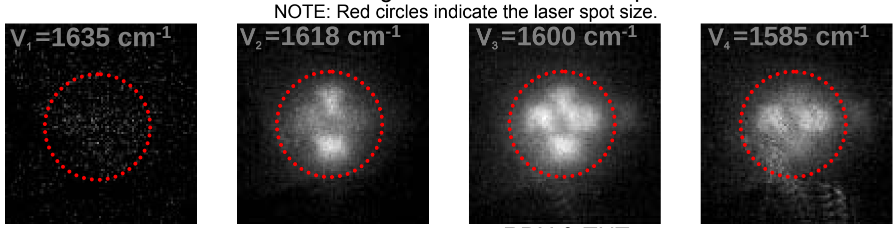


Tunable QCL from Daylight Solutions



Differential images of QCL-heated samples:

NOTE: Red circles indicate the laser spot size.



Off-resonance | TNT resonance | RDX & TNT | RDX resonance

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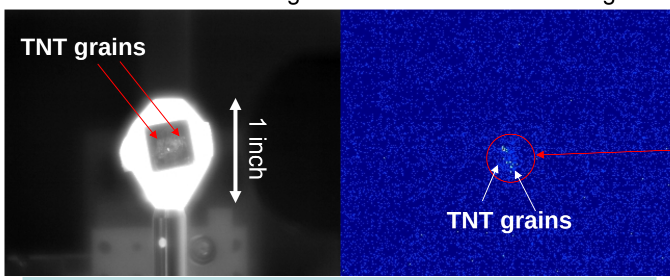
Standoff Detection of TNT

- 1 meter standoff (not limited to this distance)
- 20 mW, λ=6.25 micron, 10 mm diameter QCL beam
- ΔT is ~ 1 ^{o}C for bright grain seen in both images.
- Individual particles @ 10-100 microns (0.8 – 800 ng)

“Heat Gun” Thermal Image   Laser Differential Image



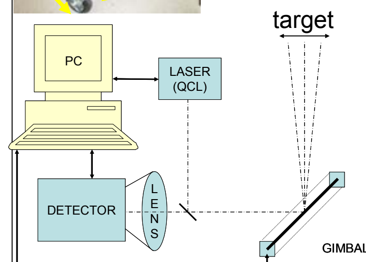
R. Furstenberg et. al, Applied Physics Letters, **93**, 224103 (2008)

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

RED cart-mounted system of integrated components for field testing.



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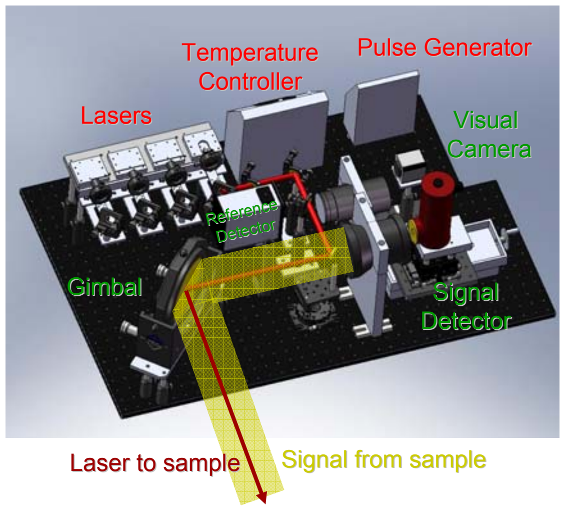
Optical Layout

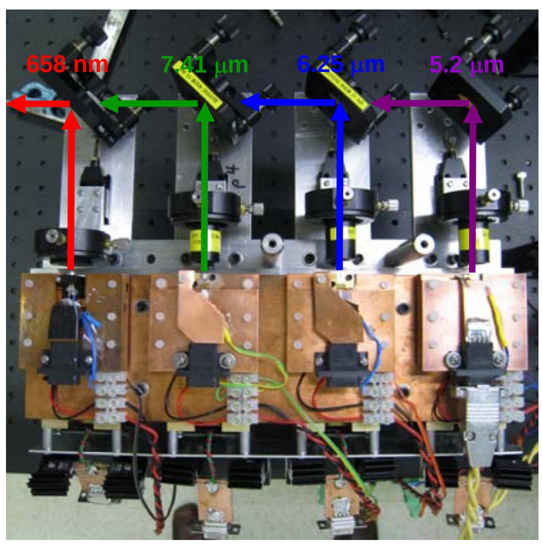
- Modular design
- Co-aligned:
  - QCL excitation
  - IR detection
  - Visible alignment
- 12 mm collimated beam for long standoff
- IR and visible imaging systems are co-focused
- Approved eye-safe for use around people by Navy Laser Safety Review Board



QCL Module Layout

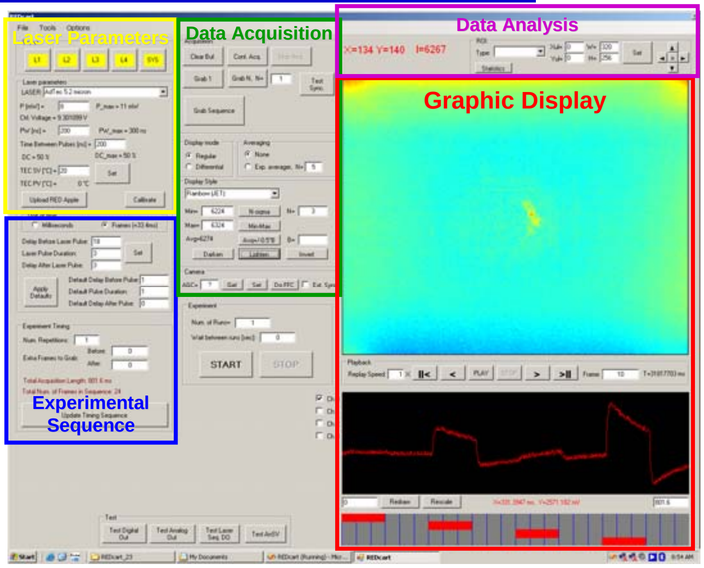
RED QCL Module

- 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



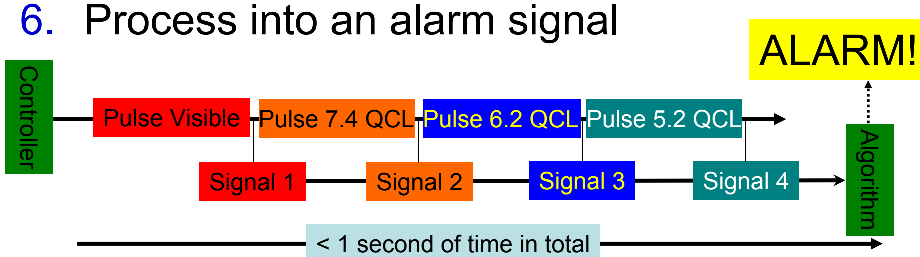
RED Cart Software Interface

- 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 λ
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

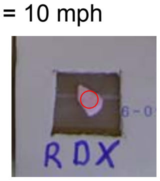


Field Testing at Yuma Proving Ground

- 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

Field Testing at Yuma Proving Ground

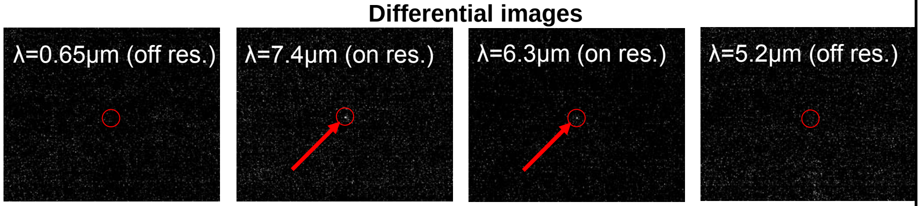
Sample: **RDX**
Stand-off distance: 10m
$T_{amb.}$ = 22 °C
RH = 13%
V_{wind} = 10 mph



← 3 inch →

RDX detected at 10 meter stand-off

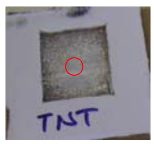
Differential images



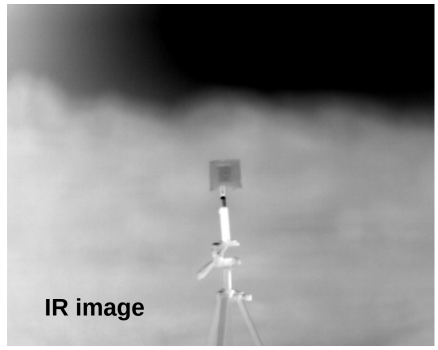
Δ=-0.04 counts | Δ=1.28 counts | Δ=1.02 counts | Δ=-0.09 counts

Field Testing at Yuma Proving Ground

Sample: **TNT**
Stand-off distance: 10m
$T_{amb.}$ = 22 °C
RH = 14%
V_{wind} = 10 mph

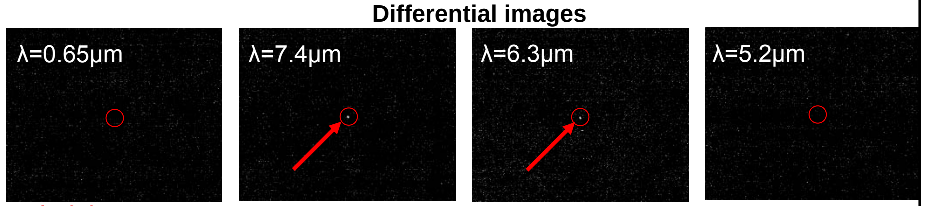


← 3 inch →



TNT detected at 10 meter stand-off

Differential images



Δ=0.07 counts | Δ=0.95 counts | Δ=1.09 counts | Δ=-0.04 counts

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

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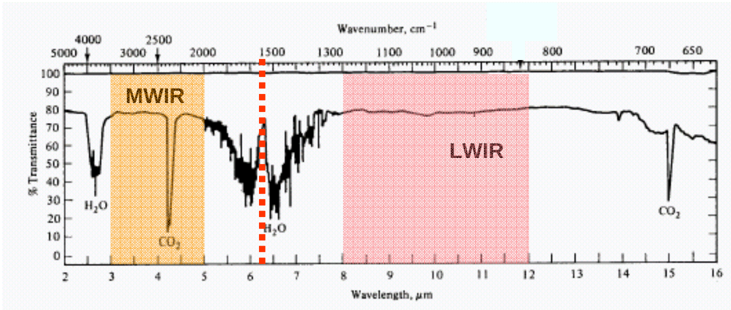
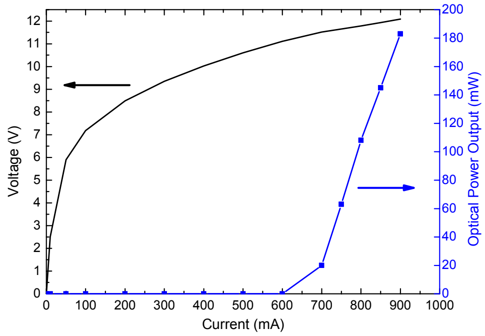
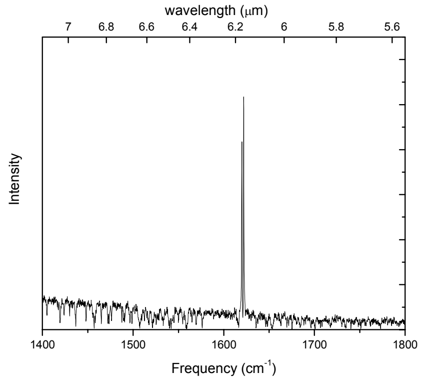
Air Infrared Transmission



- 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



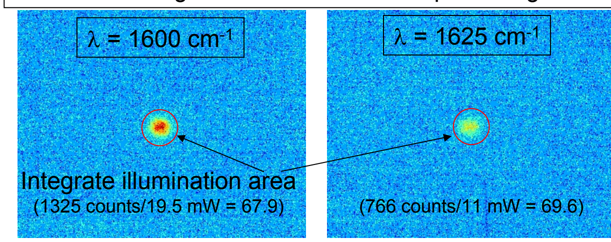


- OEM/COTS c-mounted QCL from AdTech Optics
- Operates at room temperature and slightly above
- Temperature controlled for constant output λ and power
- >180 mW Continuous Wave (higher in pulsed mode)

Interferent/“confusant” Testing

- Broadband absorbers will heat independent of wavelength.
- Distinguish this “confusant” by difference of differences
- 1325 counts/19.5mW= 67.9 (λ = 1600 cm^{-1})
- 766 counts/11mW = 69.6 (λ = 1625 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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