

# Quantum Cascade Laser (QCL) based sensor for the detection of explosive compounds

Erwan Normand\*, Iain Howieson, Michael McCulloch, Paul Black  
Cascade Technologies, Unit A, Logie Court, Stirling University Innovation Park, Stirling, FK9  
4NF, Scotland, UK

## ABSTRACT

Following Cascade Technologies first success at using Quantum Cascade Lasers (QCL) for trace gas detection in the continuous emission monitoring market, the core technology platform is now being developed towards homeland security applications.

This paper will highlight the potential of QCL based trace gas sensor for detecting vapours of explosives. Furthermore we will present results that let foresee the use of such technologies at addressing security gaps for protection against terrorism in infrastructures where high throughput screening of individuals or items is required. Preliminary measurements have shown that rapid identification, or fingerprinting, of explosive is achievable in 10ms at extrapolated sensitivities in the sub-part per billion range.

The experiments were carried out with support from the Home Office Scientific Development Branch (HOSDB) in the UK and were focused at selecting a variety of explosive compounds and showing their detection using a novel sniffer platform system based on the use of quantum cascade lasers. Preliminary studies on the technology have indicated that direct fingerprinting (detection – identification) of explosive compounds such as NG and tagging agents such as EGDN by sniffing surrounding ambient air is achievable. Furthermore these studies have also indicated that detection of such compounds on packaging used to ship the sealed compounds is possible, making this platform a strong contender for detection through cross contamination on material that have been in contact with each other. Additionally, it was also possible to detect breakdown products associated with sample material NG providing a further capability that could be exploited to enhance the detection and identification of explosive compounds.

**Keywords:** improvised explosive devices, explosive detection, Quantum Cascade Laser, mid infrared, gas spectroscopy

## 1. INTRODUCTION

Since the attacks on the United States on September 11, 2001, followed by bombings of trains and underground in Madrid and London respectively, and more recently with the 10<sup>th</sup> of August 2006 UK airport security alarm the demand for systems capable of providing early warning of an explosive attack has surged to an all time high. In addition, national governments, especially the U.S. government, have greatly increased money to be spent on research and development for new and improved technologies. In an effort to respond to the momentous increase in requirements for explosive monitoring devices, private industry as well as non-profit research institutions in the U.S. and the rest of the world are gearing up to serve this expanding market. Within the EU priorities in that aspect were expressed in various reports<sup>1</sup> the last call of the PASR 2006 part of FP6. The missions were:

- “Protecting against terrorism (including bio-terrorism and incidents with explosives biological, chemical and other substances)”
- “Technologies for protection and countermeasures against the impact of explosions.”
- “Enhancing Crisis Management (including evacuation, search and rescue operations, control and remediation)”

Today techniques for improvised explosive devices (IED) is seen as key development in many civil applications where the ability to identify and quantify hazardous materials can provide advanced warning of potential dangers allowing evacuation and counter measures to be employed. Traditional detection methods for these materials such as Ion mobility spectroscopy<sup>2</sup> (IMS) and Gas Chromatograph Mass Spectroscopy (GCMS) do not lend themselves to ease of deployment in various scenarios and high throughput screening of individuals or packages together with high sensitivities and low false alarm rate.

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\* [e.normand@cascade-technologies.com](mailto:e.normand@cascade-technologies.com); phone +44 (0)1786 447721; fax +44 (0)1786 475822; [www.cascade-technologies.com](http://www.cascade-technologies.com)

Optical IR spectroscopic techniques such as Fourier Transform Spectroscopy<sup>3</sup> (FTS) or Laser Absorption Spectroscopy<sup>4</sup> (LAS) have been employed for many years in fields such as Astronomy and Metrology to help understand the constituents and make up of the atmosphere of the earth, the planets and the stars. As such they are well suited to the detection of various compounds; however, these techniques have not commonly been applied to explosive (E) and chemical agent (C) detection due to the lack of sensitivities, robust systems.

We describe below a quantum cascade laser (QCL) based gas sensing technology that has the capability of detecting explosive compounds at atmospheric pressures and ambient temperatures.

## 2. CORE TECHNOLOGY DESCRIPTION

Conventional semiconductor lasers, such as the lead salt devices commonly used in the mid-IR, rely on electron hole recombination across the doped semiconductor bandgap to emit photons. The quantum cascade laser operates on a fundamentally different principle whereby electrons cascade down a series of quantum wells, which result from the growth of very thin layers of semiconductor material. Whereas a single electron-hole recombination can only ever produce a single photon, the quantum cascade laser electron can cascade down between 20 and 100 quantum wells producing a photon at each step. This electronic waterfall provides a step change in performance in terms of lasing efficiency enabling QCL to emit several watts of peak power in pulsed operation and tens to hundreds of milli-watts CW.

The lasing wavelength for QCL is determined not by the choice of semiconductor material as with conventional lasers, but by adjusting the physical thickness of the semiconductor layers themselves. This removes the material barriers commonly associated with conventional semiconductor laser technology and opens up the possibility of near-infrared through to THz spectral coverage. For the first time an infrared spectroscopic laser source, which has no need for cryogenic cooling, high output powers, large spectral coverage, excellent spectral quality and good tuneability has become a reality.

The practical implementation of QCL in spectroscopy started in earnest in the late 1990's with researchers eager to harness the power of a spectroscopic source spanning the full spectrum of the technologically significant mid-IR wavelengths (3 - 25  $\mu\text{m}$ ). Two methods of direct absorption spectroscopy have resulted from this research. Known as inter and intra pulse spectroscopy respectively they have been developed to maximise the performance of the QCL as a spectroscopic tool.

Inter pulse spectroscopy<sup>5</sup> uses the QCL in pulsed mode to facilitate its use at or close to room temperature. The optical transmission is recorded by combining ultra short current pulses to the laser with a slowly varying current or temperature ramp superimposed to tune the laser wavelength through the spectroscopic transition of interest. However, it was found that pulsing the laser in this way resulted in a frequency chirp and consequently a broadening of the laser linewidth and a reduction in spectral resolution. To help overcome this effect it was necessary to limit the pulse width to less than a few tens of ns whilst keeping the pulse amplitude close to the lasing threshold. The typical tuning range for this technique is of the order of 1 to 2  $\text{cm}^{-1}$  with repetition rates ranging from tens of Hz through to kHz.

Inter pulse has been employed with considerable success in spectroscopy. However, the threshold current limitation, the introduction of noise due to ultra short pulse to pulse variability and the lower duty cycles attainable have prevented inter pulse spectroscopy from achieving the very highest level of sensitivity currently available to other spectroscopic techniques.

Intra pulse spectroscopy<sup>6</sup>, like inter pulse, uses the laser in pulsed mode to effect room temperature operation. However, rather than trying to minimise the frequency chirp brought about by pulsing the QCL, the chirp is instead harnessed to provide a near instantaneous frequency sweep through the spectroscopic features of interest. Pulse widths up to several micro seconds are employed with pulse amplitudes several amps above lasing threshold to produce a top hat current pulse that causes localised heating within the laser and consequently a frequency downchirp, which is typically between 4 and 10  $\text{cm}^{-1}$  wide (see figure 1). The spectral resolution in this case is defined by the instantaneous linewidth of the laser as it sweeps in wavelength. This is simply given by:

$$\Delta\nu = \sqrt{k \frac{d\nu}{dt}}$$

where  $dv/dt$  is the chirp rate and  $k$  is a form factor defined by the pulse shape<sup>7</sup>. Typical QCL frequency downchirps will normally have better than  $0.01\text{cm}^{-1}$  spectral resolution (see figure 2). This is better than the inter pulse technique for the same chirp rate. Repetition rates of up to 1 MHz can be used giving high duty cycles and the resulting spectra averaged to provide excellent S/N levels.

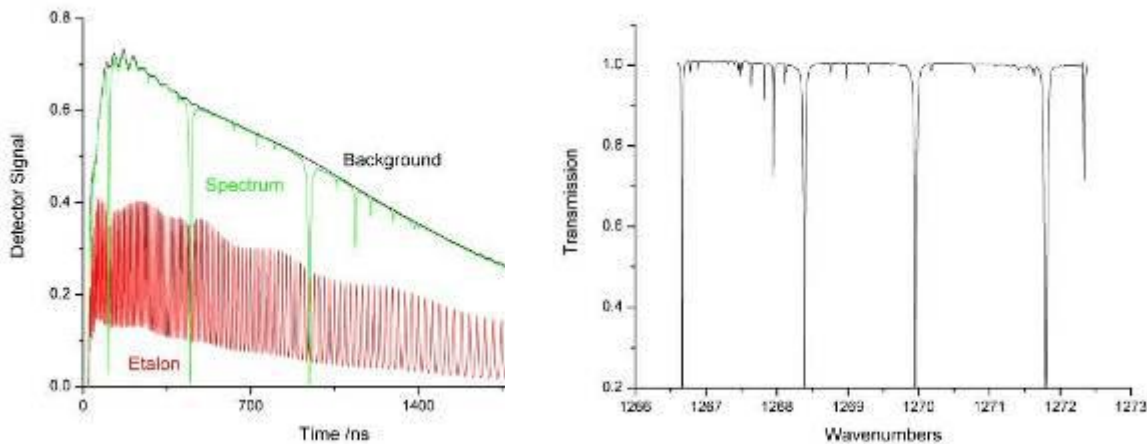


Figure 1. Raw Data, Background and Transmission spectra of room air recorded using a  $1270\text{ cm}^{-1}$  QCL with Intra Pulse Spectroscopy. A 2000 ns pulse is applied to the laser resulting in a frequency chirp, which sweeps the laser through the spectroscopic transitions of interest. A  $0.048\text{ cm}^{-1}$  Ge etalon signal confirms greater than  $6\text{ cm}^{-1}$  single mode tuning.

Operating the laser in this quasi CW intra pulse regime provides another less obvious but significant spectroscopic advantage. The fast chirp rate can be used in conjunction with careful optical design to ensure incoherent optical feedback<sup>8</sup>. This is used to prevent laser feedback noise and optical fringing, which tend to be the common noise floors for most practical implementations of optical spectrometer design. The removal of this noise floor, without the need of complex fringe removal techniques such as Brewster Plate spoilers or expensive optical isolators, enables the laboratory performance of this technology to be easily transferred to real world applications. Cascade has patented the use of the intra pulse technique and the key technological advantages it provides.

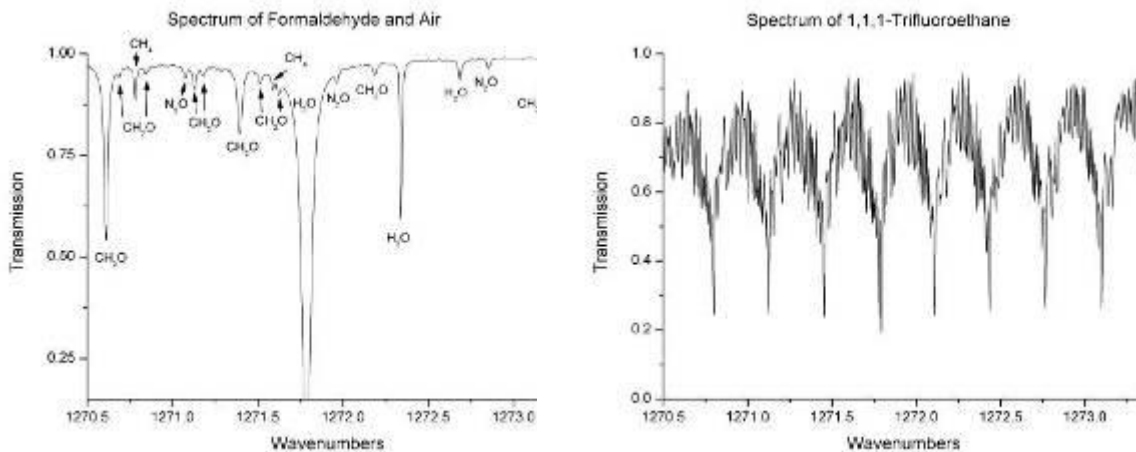


Figure 2. Recorded spectra of Formaldehyde and 1,1,1 Trifluoroethane. These spectra highlight the excellent S/N and selectivity that can be achieved with the QCL and Intra Pulse Spectroscopy. Key features such as intrinsically fringe free operation and better than  $0.01\text{ cm}^{-1}$  spectral resolution provide a powerful fingerprinting capability.

The intra-pulse technique can also be used with Fabry Perot structures to extend the wavelength coverage given by the QCL. This is shown schematically in figure 3. Multi-mode QCL have recently been demonstrated with large spectral emission<sup>9</sup> extending beyond  $300\text{ cm}^{-1}$ . This broadband coverage, whilst maintaining the key attributes of a coherent laser source, can bring significant advantages to the detection of trace gases.

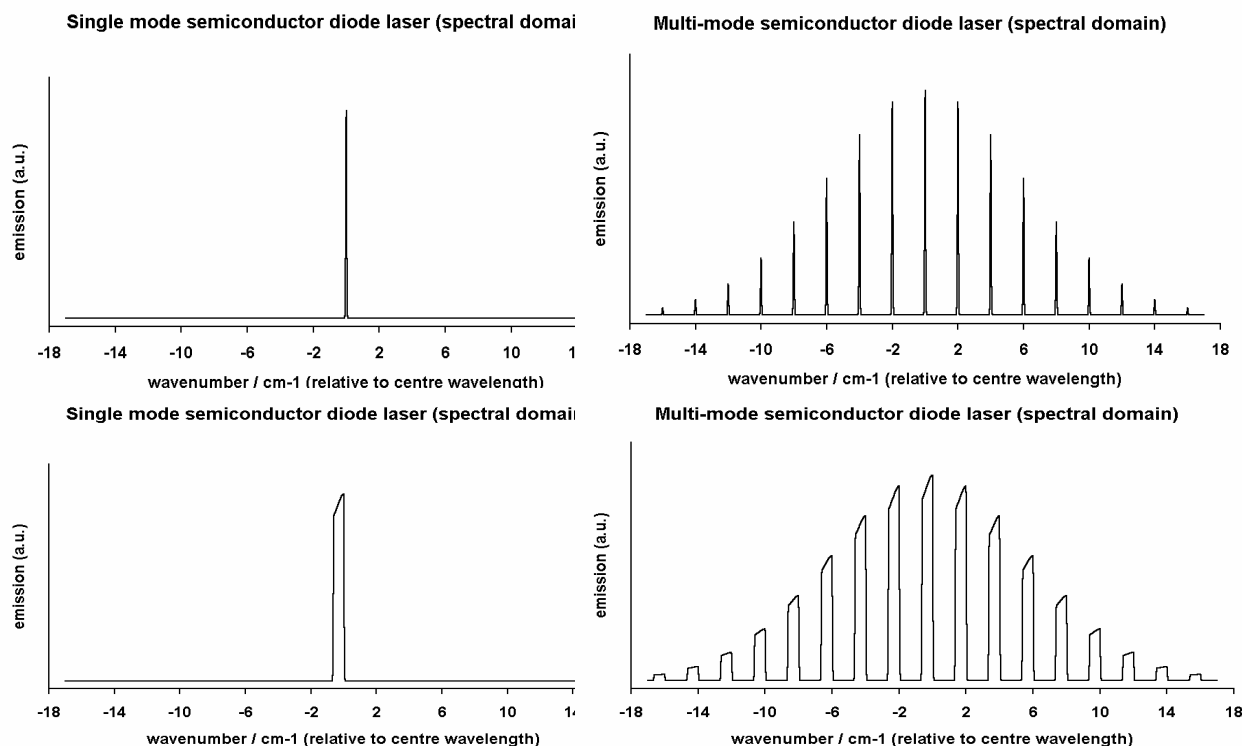


Figure 3. The spectral emission from single and multi-mode QCL with and without the Intra pulse technique. The use of multi longitudinal mode lasers can extend wavelength coverage of QCL to over  $300\text{ cm}^{-1}$ .

### 3. PROOF OF CONCEPT FOR EXPLOSIVE DETECTION

The explosive detection program described below was realised with support from the Home Office Scientific Development Branch (HOSDB) in the UK and was carried out in two stages. The first phase covered the acquisition and analysis of high resolution gas phase spectra of 6 different compounds selected by HOSDB.

The second phase concerned the feasibility study on the application of QCL for compound detection. The high resolution Fourier Transform Infrared (FTIR) spectra recorded in the first phase have been analysed to identify suitable regions for detection with the QCL based gas sensor. This information has been used to enable the detection and analysis of explosives/taggants at trace level at room temperature.

#### 3.1 Explosive sample preparation and Knowledge

The spectroscopy of explosive or IED compounds is different from that of most common atmospheric gases in that explosives are typically made up from complex large heavy molecules. These molecules don't provide individual isolated absorption features, which would allow unambiguous characteristic fingerprinting, but instead the many degrees of freedom afforded by such molecules gives heavily blended features made up of thousands of individual rotational vibrational transitions. The spacing of these transitions is such that even at very low pressures no separation is observed. These broadband transition features have precluded measurement with lasers in the past due to their limited tuning capability.

Cascade Technologies has been able to utilize its patented QCL gas sensing techniques combined with the generation of high resolution chemical fingerprints to demonstrate unambiguous diode laser fingerprinting and detection of explosive compounds for the first time.

A key component of IED detection is the generation of the fingerprint database for the compounds of interest. Historically, due the broadband spectroscopic nature of these compounds, fingerprints have been carried out at low resolution ( $1$  to  $16\text{ cm}^{-1}$ ) using FTIR spectrometers. For confidentiality reason this paper will not show figures with absolute wavelength (or wavenumber) scales, but typically the spectral region of interest will range from  $2000\text{ cm}^{-1}$  to  $800\text{ cm}^{-1}$ . During this explosive study we found that high resolution ( $<0.1\text{ cm}^{-1}$ ) spectra of these compounds are necessary if fingerprinting of these compounds with lasers is to be successful. An example of the high resolution infrared fingerprint of PETN, a well known plastic explosive, is shown in figure 4.

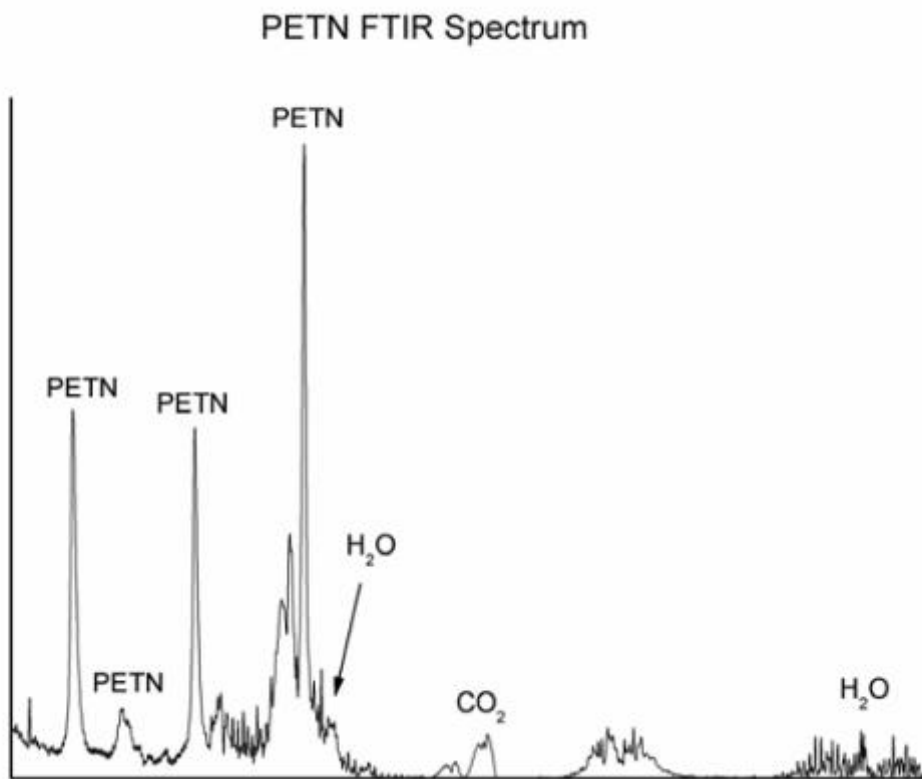


Figure 4. Fingerprint spectrum of PETN recorded on a high resolution ( $0.05\text{ cm}^{-1}$ ) Fourier Transform Spectrometer

In the first phase of the study we covered the acquisition and analysis of high resolution gas phase spectra of several different explosive compounds. These spectra were recorded using a high resolution Fourier Transform Infrared Spectrometer (FTIR) and allowed a spectroscopic database to be generated for the compounds of interest. The role of the database is to establish the explosive and IED fingerprint knowledge for detection with QCL and to form the basis for selecting the required laser emission wavelength for their subsequent integration into the detection platform.

Analysis of the high resolution FTIR spectra has allowed transition frequencies, band strengths and spectroscopic assignments to be made for the compound listed below.

- 2,3-dimethyl-dinitrobutane (DMNB)
- Trinitrotoluene (TNT)

- Ethylene Glycol Dinitrate (EGDN)
- Hexahydro-1,3,5-Trinitro-1,3,5-Triazine (RDX)
- Pentaerythritol tetranitrate (PETN); shown above
- Nitroglycerine (NG)

Some of the key IED compounds, not listed above, such as Triacetone Triperoxide (TATP) and Hexamethyl Triperoxide Diamine (HMTD) could not at the time be analysed as they are highly unstable materials.

To minimise the chance of cross contamination the samples of explosive and IED were prepared by HOSDB in the form of powder or dry residue and stored in sealed glass containers which in were sealed in aluminium vacuum bags in a fume cupboard.

In order to carry out the high resolution (HR) spectral analysis, we used the FTIR equipment at the MSF facility, Rutherford Appleton Laboratory in the UK. Specialised sampling kit for explosive fingerprinting (see figure 5) was also developed to be used with the FTIR spectrometer. The instrument used to record the spectra was a Bruker Optics IFS 120HR Fourier Transform Spectrometer, which has a maximum unapodized spectral resolution of  $0.0015 \text{ cm}^{-1}$ . It has a spectral range of  $30 \text{ to } 40000 \text{ cm}^{-1}$ , achieved through a combination of sources, beam splitters and detectors. The spectrometer is evacuable with a turbo-molecular pump, significantly reducing absorption from water vapour and carbon dioxide within the optics compartments. Figure 6 below shows a picture of the Bruker Optics IFS 120HR Fourier Transform Spectrometer at RAL.

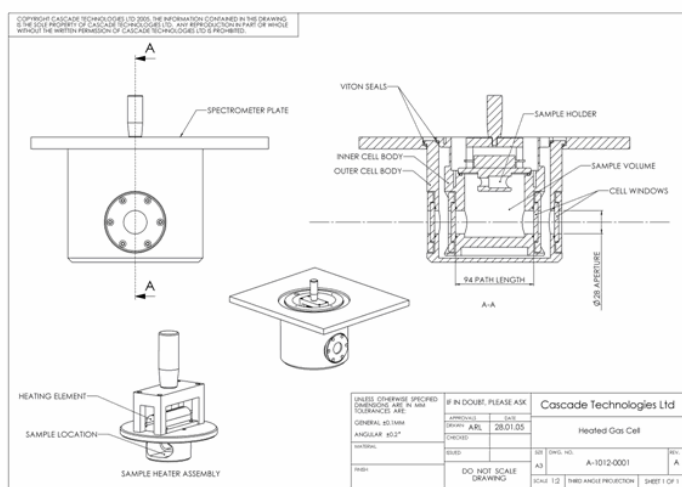


Figure 5. Drawing of the custom designed heated sample cell for explosive gas phase measurements at RAL using the Bruker IFS 120HR Spectrometer

Figure 6. The Bruker Optics IFS 120HR Fourier Transform Spectrometer at Rutherford Appleton Laboratory

During measurements it was possible to heat the gas sample cell tubing and inside sniffing plate to observe platform performance versus sample temperature since the vapour pressure from sample materials will increase with temperature. Vapour phase pressures have been calculated using the Clapeyron-Clausius equations.

$$\frac{d \ln p}{dT} = \frac{\Delta H_{sub}}{RT^2}$$

The key conclusions from this high resolution analysis were:

- High resolution data provides significantly better definition of the spectroscopic envelopes of each vibrational transition. This added definition is key in helping to unambiguously identify each compound with a diode laser;

- Pressure and Temperature Broadening effects for these compounds is insignificant at atmospheric pressures and temperature therefore sensitivity and fingerprinting capability should be unaffected by open path remote detection techniques;
- The strongest fingerprints for these complex heavy molecules are found between wavelength of 5 and 12.5 $\mu\text{m}$ , the sweet spot of QCL emission coverage;
- High resolution FTIR fingerprints provide a complete understanding of associated breakdown products for compounds of interest. This breakdown information can be used to further aid compound identification.

### 3.2 Laser selection

The second phase of the study was covering the feasibility study on the application of QCL for explosive and IED compound detection. The information obtained during the first phase has been used to modify the existing laboratory gas sensor at Cascade Technologies to enable the detection and analysis of explosives and IED at trace level and at room temperature. The high resolution FTIR spectra recorded at RAL enabled the determination of suitable wavelengths for detection of the explosive compounds. A suitable spectral region was identified targeting EGDN, NG, TNT and RDX, all having strong features in the same region.

A survey of available stock, from commercial manufactures showed that a device operating in the region of interest were available. The laser was single mode at room temperature. Utilising Cascades patented chirp technique, to enhance the wavelength tuning of the device up to 10  $\text{cm}^{-1}$ , ensured that the laser covered the spectral region of interest.

### 3.3 Sensing platform

A prototype laboratory demonstrator QCL gas sensor was developed (see figure 7) and was used to record the vapour phase spectra of explosives and IED at room temperature. The spectrometer measures the absorption caused by the interaction of light with molecules in the gas phase as described above in the core technology description.

Operating in the intra pulse regime, wavelength tuning up to 10 $\text{cm}^{-1}$  is possible. The sensor was also designed to enable the easy swap in/ swap out of alternative laser heads if extended wavelength coverage was necessary. The sensors ability to record a background signal and detector zero during each measurement provides a simple absolute measurement of the sample gas concentration. Spectral resolution is dependent on the laser chirp rate but is typically better than 0.01  $\text{cm}^{-1}$  as described earlier. The control electronics, optical sub systems and software are proprietary and exploit over 20 man years of QCL experience gathered at Cascade Technologies.



Figure 7. Example of Prototype Laboratory Demonstrator Gas Sensor developed at Cascade Technologies .Cascades' proprietary control electronics and software exploit the key advantages provided by its patented intra pulse technique.

The layout of the spectrometer is minimised to ensure robust repeatable measurements. In its most basic form it consists of the source (QCL), sample cell and detector. Collimated light from the QCL head enters a multipass cell. The enhanced pathlength (238 passes give 76 meters) combined with the short optical train outside the cell provides excellent sensitivity and discrimination for targeted species. Light exiting the cell is focused down onto a room temperature MCT detector. The QCL itself is typically operated at 10–15 deg C, however, temperatures in the range -45 to +50 deg C can be obtained via integrated Peltier element. Changing the base temperature of the laser enables the centre frequency of the device to be shifted by  $\pm 5 \text{ cm}^{-1}$  where required.

### 3.4 Sampling

The gas sample is evacuable and can be purged regularly to minimise memory effects. The vacuum system combines a compact rotary pump, pressure controller, pressure sensor and inlet manifold. Specialised tubing material is used to link the sample cell inlet manifold to for example a perforated sniffing probe.

The cell operated in a continuous flow cycle where the pressure controller allowed constant pressure to be maintained within the sample cell. Since the core platform is relatively insensitive to optical fringing, the sample cell volume was reduced to much less than 0.5l allowing fast flow rate and ensuring that the dwell time within the cell was minimised. The cell can also be operated in static sample conditions.

## 4. RESULTS

The vapour phase spectra of NG and EGDN explosive/taggants are presented here. For each compound a spectral analysis and cross comparison high resolution FTIR data, recorded in the first phase, has been completed. This has enabled fingerprint and performance assessments for each species to be made.

#### 4.1 Test with EGDN and NG samples

Preliminary measurements of explosive materials have been achieved by directly sampling the explosive itself but also looked at sampling potentially cross contaminated materials or body (packages, hands).

As described in the first phase, in order to minimise the chance of cross contamination the samples will be prepared and stored in sealed glass containers which in turn will be sealed in aluminium vacuum bags in a fume cupboard.

An example of the fingerprints of NG and EGDN at room temperature and atmospheric pressure and the inter-comparison with the FTIR data is shown in the figure 8 below.

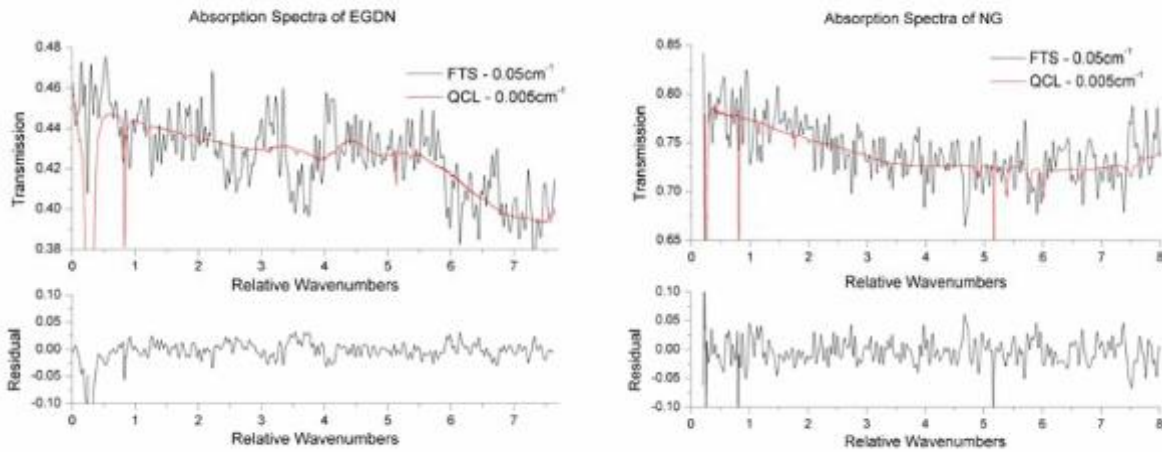


Figure 8. Inter-comparison between the QCL spectrum of EGDN and NG and the high resolution FTIR data Measured RMS residuals are within the noise of the FTIR measurement

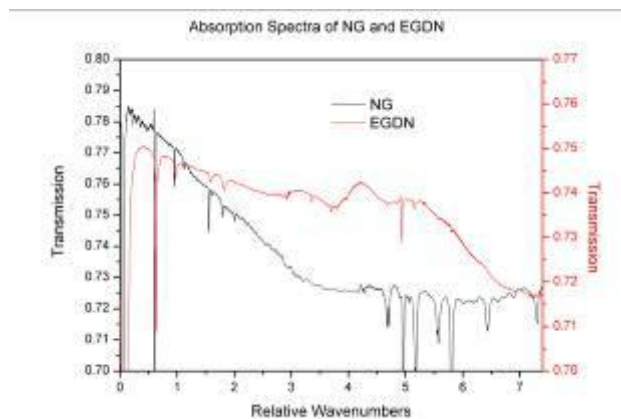


Figure 9. High Resolution QCL Fingerprints of EGDN and NG achieved with the same laser. The distinct signature for each compound gives confidence over the fingerprinting capability of the QCL gas sensor.

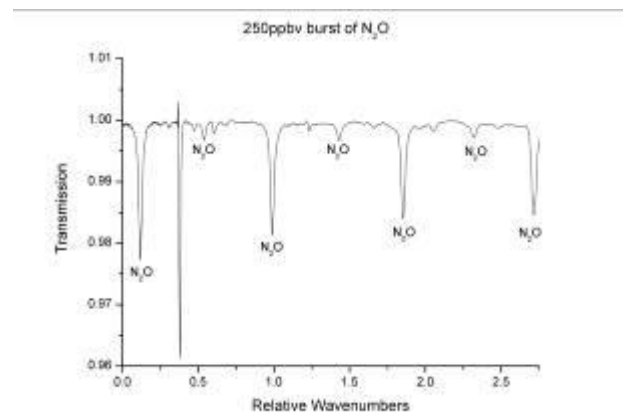


Figure 11. Trace detection of breakdown products ( $N_2O$ ) which was associated with sample material (NG) sealed in glass containers provides an additional capability that could be exploited to further aid the detection and identification of explosive compounds.

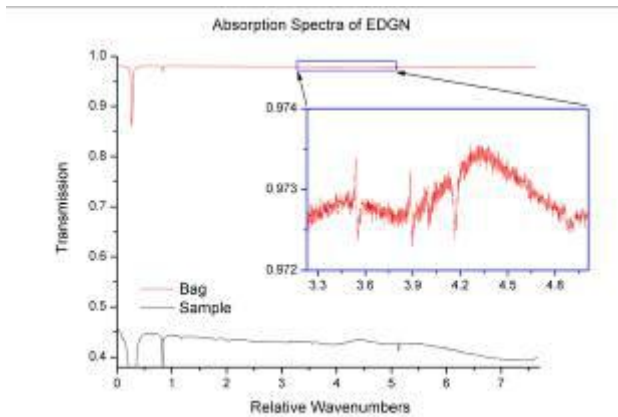


Figure 10. EDGN fingerprints were detected on the packaging material used to ship the sealed glass sample container. A comparison between this fingerprint and the pure sample shown above highlights the characteristic Sine signature associated with this material.

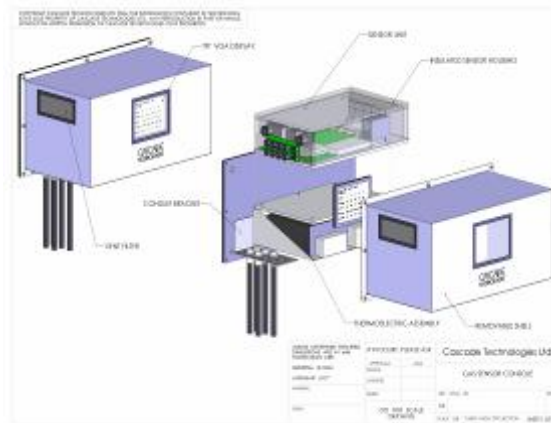


Figure 12. Example of productionised sensor unit developed at Cascade Technologies for the Continuous Emission Monitoring Market. Cascades proprietary control electronics and software exploit the key advantages provided by its patented intra pulse technique.

#### 4.2 EDGN Sensitivity

Figure 9 shows part of the broadband feature associated with the EDGN sample. This corresponds to a 500 ppbv partial pressure of EDGN in the sample cell. This figure has been calculated using the band strength data gathered in the first phase of the project and is well below the Clapeyron-Clausius vapour pressure estimate of 40 ppmv at the same temperature. However, the vapour pressure of EDGN is notoriously difficult to estimate and will depend very much on its age and the matrix it is suspended on.

The spectrometer was also used to measure EDGN on the glass sample container before it was opened and the empty aluminium vacuum bag that had been used to ship the sealed glass container. In each case EDGN spectra were observed. Figure 10 shows a comparison between the spectrum of the pure EDGN sample and the spectrum obtained from the empty aluminium bag. The expanded region highlights the characteristic high frequency SINE signature of EDGN from the bag. This fingerprint is equivalent to a EDGN partial pressure of 25 ppbv.

The EDGN data presented here is an average of 2500 one microsecond spectra recorded over a 10 millisecond interval. To determine the extrapolated detection sensitivity we have assumed a 1 HZ measurement bandwidth, 76 meter pathlength and a S/N ratio of 1. Under such conditions a minimum detectable absorption of approximately  $5 \times 10^{-5}$  is exhibited. This would correspond to a 25 pptv EDGN detection limit. This limit does not take into account the effect of losses at the inlet probe and sample cell.

#### 4.3 NG Sensitivity

Figure 9 also shows part of the broadband feature associated with the NG sample. This corresponds to a 200 ppbv partial pressure of NG in the sample cell. Again this has been calculated using the band strength data gathered in the first phase of the project. The Clapeyron-Clausius vapour pressure estimate is 400 ppbv at the same temperature. The discrepancy might be accounted for by losses at the inlet probe and sample cell which were unheated.

The sensor was also used to sample the aluminium vacuum bag when it was first opened. Interestingly a large increase in the  $N_2O$  concentration was observed. This is shown in figure 11. The peaks correspond to 250 ppbv increase in the  $N_2O$  concentration above typical ambient levels (300 ppbv). It is thought that these elevated levels are caused by the partial breakdown of the NG sample within the sealed glass NG container. The ability of the system to detect such breakdown products, at high sensitivity, could potentially be exploited as an additional tool for the detection and identification of explosives.

Again The NG data presented here is an average of 2500 one microsecond spectra recorded over a 10 millisecond interval. To determine the extrapolated detection sensitivity we have again assumed a 1 HZ measurement bandwidth, a 76 meter pathlength and a S/N ratio of 1. Under such conditions a 50 pptv detection limit is predicted. This limit does not take into account the effect of losses at the inlet probe and sample cell.

## 5. SUMMARY

Trace EGDN and NG room temperature spectra have successfully been recorded with Cascades QCL based spectrometer operating at mid infrared wavelength. Comparison with high resolution FTIR spectra, recorded during in the first phase is excellent. The presence of atmospheric constituents such as H<sub>2</sub>O and N<sub>2</sub>O has shown that discrimination between the EGDN or NG sample and these potential interferers is good. The demonstration of EGDN detection from packaging material used to ship the sealed glass sample containers has highlighted the sensitivity of the instrument, which is extrapolated to be better than 25 pptv. Regarding NG, the extrapolated sensitivity from the measurements would indicate a 50 pptv detection limit. Furthermore the demonstration of trace detection of breakdown products (N<sub>2</sub>O), associated with the sample material NG, provides additional capability that could be exploited to help detect and identify explosive compounds.

The results of these measurements have shown that:

- QCL detection is over 1000 times more sensitive than FTIR measurements with PPT detection sensitivities extrapolated. This sensitivity has been highlighted by the ability to detect explosives or IED on packaging used to ship trace levels of explosives.
- Fingerprinting was achieved in 10ms compared to 8 hours with a high resolution FTIR.
- QCL fingerprints can be taken near instantaneously at high resolution (<0.005 cm<sup>-1</sup>).
- Common explosive compounds such as EGDN, TNT, PETN, RDX, NG and DMNB can all be unambiguously fingerprinted with QCL.
- Simultaneous measurement of breakdown products with a QCL, can significantly aid fingerprinting.

## 6. FUTURE PRODUCT

The performance, cost, size and weight of a commercial trace explosive QCL based sensor have been considered. The performance of such an instrument can be assessed by two key criteria:

- The detection capability of the Sensor
- The fingerprinting capability of the Sensor

The extrapolated detection limits of the QCL based sensor for the six compounds listed above, measured in the first phase, have been calculated. These figures have been derived from the band strength information gathered during the first phase of the project and the QCL spectra of EGDN and NG recorded in the second phase. While these QCL measurements have been taken in a laboratory, Cascade is confident that the sensitivity can be transferred to a real world environment. This confidence has been gained by trial installations of the same platform in the continuous emission monitoring sector over the past 18 months. A conservative factor of ten has been applied to the ultimate sensitivity figures to provide additional confidence in terms of deliverable commercial instrument performance. In this case all six compounds would still have a detection limit below single PPB levels. In order to achieve this sensitivity, however, further development of the sample cell and inlet probe, to reduce losses, would be required.

The fingerprinting capability of the QCL gas sensor is an important requirement in minimising false positives. Spectral data in the spectral band of interest has shown that there is little cross interference from abundant atmospheric constituents such as H<sub>2</sub>O, CO, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O etc. It is also evident that the signatures of these compounds are very different to those obtained from the EGDN and NG samples. This would give confidence regarding discrimination from common interferers.

If we consider the signatures of EGDN and NG, as shown in figure 9, it is clear that both are distinct. Based on these signatures Cascade is extremely positive regarding unambiguous fingerprint identification.

FTIR data of two other compounds that also absorb in this spectral region, namely RDX and PETN also showed quite distinct signatures. Cascade believes, therefore, that unambiguous fingerprinting of these four compounds could be possible with a single headed QCL operating in the spectral region of interest.

The two other compounds that have so far not been considered in terms of fingerprinting are DMNB and TNT. However data results from the first phase indicate that both these compounds could be simultaneously measured at a different spectral band. In this case an additional laser would be required. As such Cascade is modifying the design of an existing multi laser gas sensor (see figure 12). As for future development work Cascade Technologies is now focusing at further validating these measurements with additional focus on detection limit, sampling methods and expanding its explosive database.

### ACKNOWLEDGEMENT

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