Single Snapshot Standoff Detection Using Sub Microsecond Tuning Speed Quantum Cascade Lasers

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1. Introduction

Infrared spectroscopy has proven to be an excellent tool for identifying and quantifying gases, liquids and solid samples. For many applications, tunable laser based systems are displacing the traditional FTIR spectrometry, which utilizes black body radiators as the sources of broadband infrared radiation. Even though the laser-based systems are generally more expensive and not quite as versatile as the FTIR systems, they provide unique advantages of higher powers, better resolution, speed and a capability for projecting the interrogating light beam over long distances. Being able to project optical radiation over long distances provides infrared spectroscopy a special advantage over all other methods for detection and quantification of remote targets. All other techniques, including mass spectrometry require the instrumentation to be in close proximity of the target being interrogated. Of all laser based spectroscopy schemes, the mid wave infrared (MWIR) and long wave infrared (LWIR) regions have proven to be very effective for laser based systems, because most if not all relevant undesirable targets (gases, liquids and solids) have strong and well characterized absorption signatures in these regions and because, in general, MWIR and LWIR laser radiation is eye safe because of strong absorption by liquid water.

2. Tunable Infrared Lasers and QCLs

Tunable MWIR and LWIR lasers include optical parametric oscillators, semiconductor junction lasers, molecular gas lasers such as carbon dioxide and carbon monoxide lasers and quantum cascade lasers. Of these, the gas lasers can be tuned only at discrete wavelengths because the laser emission occurs on molecular vibrational-rotational transitions. Of the remaining types, OPOs are secondary lasers, which require to be optically pumped by another laser source, and thus are generally less desirable. The semiconductor junction lasers and QCLs are primary lasers that convert electrical power directly into laser radiation and being semiconductors, they enjoy the benefits of small size and weight. The semiconductor junction lasers (often called diode lasers) require cryogenic cooling for operation at wavelength longer than about 2.0 μm, and thus are inappropriate for many practical applications. Quantum cascade lasers, because the reasons discussed, have proven to be ideal sources for MWIR and LWIR spectroscopy.

As with other semiconductor based laser gain media, QCL produces gain over a broad range of wavelengths and in a Fabry-Perot geometry, the laser emission

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occurs over >300 nm bandwidth, centered around the nominal design wavelength of the laser. For spectroscopy applications, such a laser needs to be made monochromatic and tunable (over the gain bandwidth afforded by the QCL). Traditional way of making tunable QCL involves incorporating a wavelength dispersive device, such a diffraction grating or a tunable etalon within the optical cavity. Of these two, grating tuned quantum cascade lasers have been most widely deployed because of the simplicity of construction and long history of grating tuned lasers covering UV, visible and infrared spectral regions Such QCL systems have provided the needed tunable laser radiation covering ~3.5 μm to ~12.0 μm and are the most commonly available systems.

Diffraction grating tuned systems, however, suffer from several critical disadvantages, including relative slow speed of scanning wavelengths or switching wavelengths, susceptibility to vibration and shock because of a macroscopic object, a diffraction grating, that needs to be angle tuned, and need for different diffraction gratings for covering different wavelength regions. There is an urgent need for fast tuning and ruggedness, which the grating tuned QCLs lack. Fast tuning is especially needed when one needs to obtain a compete spectral plot of transmission or absorption property of the object being examined in a time shorter than the time in which the spectra may be changing, such as when exploring combustion and explosion dynamics. Another area where rapid spectral property determination is required is standoff detection of improvised explosive devices (IEDs) in a battlefield environment. Consider a vehicle carrying soldiers travelling at a speed of ~30 kph along a highway and a strange object is seen at some distance, 50 meters, say. Should the vehicle stop or proceed? The vehicle will travel 50 meters in ~6 seconds. Thus, the driver needs to make a decision to stop or to proceed in a fraction of a second. With a rapidly tunable laser system one can take a "snapshot" of the object's surface to determine if there is an explosives residue on the surface. Only a fast scanning laser system can provide the needed answer and save lives.

We have achieved the necessary breakthrough in both of these areas, speed and ruggedness, which make such tunable QCLs extremely desirable for many practical applications that could not be addressed using the traditional grating tuned QCLs.

3. All Electronic Tuning of QCLs: Tuning Properties

We have used acousto-optic modulator (AOM) for ultrafast tuning of QCLs [1, 2]. We have achieved wavelength switching speeds of <700 ns for switching between any wavelengths within the lasing region of the quantum cascade laser (see Figure 1).

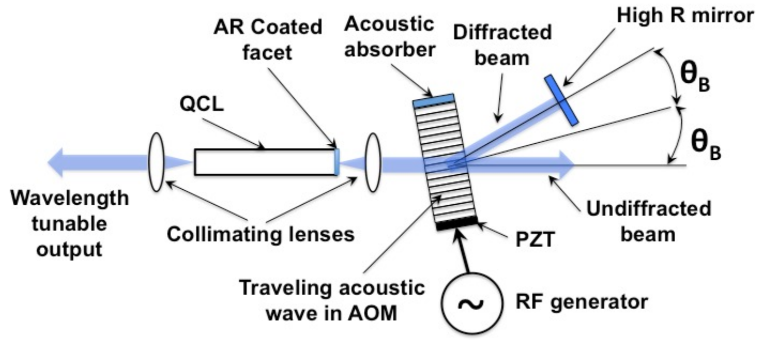

Figure 1. Schematic of a travelling wave acousto-optic modulator tuned quantum cascade laser in Littrow configuration [1]

The PZT converts applied RF into an acoustic wave, which is launched in the AOM crystal (germanium for the LWIR operation), creating a phase grating whose wavelength is determined by the acoustic velocity in the AOM crystal and the AOM drive frequency. Optical radiation crossing the acoustic wave is diffracted by the phase grating at the Bragg diffraction angle θ_B is given by,

$$\begin{aligned}\sin\theta_B &= \frac{mn\lambda_0}{\Lambda} \\ &= mn\lambda_0\frac{f_a}{v_a} \\ &= mn\frac{c}{f_o}\frac{f_a}{v_a} = mn\frac{c}{v_a}\frac{f_a}{f_o}\end{aligned} \tag{1}$$

where m is the order of diffraction, n is the optical refractive index of the AOM material, λ_0 is the optical wavelength, Λ is the acoustic wavelength, f_a is the AOM drive frequency, v_a is the acoustic velocity in the OM material, f_o is the optical frequency and c is the velocity of light . For an optical wavelength, λ_0 = 10 µm, refractive index of ~4.0 for the germanium AOM crystal, and an acoustic wavelength of ~135 µm (assume an acoustic driving frequency of 35 MHz), we get a diffraction angle of θ_B = ~7.5°. Taking m = 1, we also see (Eq. 2) that if we keep the location and angle θ of the high reflectivity mirror (Figure 1) fixed, changing of the AOM drive frequency linearly changes the laser frequency:

$$f_o = \frac{n}{\sin\theta}\frac{c}{v_a}f_a \tag{2}$$

The high reflectivity mirror set in the correct location and angle reflects the diffracted beam back into the AOM crystal providing selective feedback to the laser cavity. It should be emphasized that the location and the angle of the high reflectivity mirror can be ruggedly fixed since the tuning is accomplished by simply changing the electronic RF drive frequency to the AOM crystal, which makes for a very rugged system, immune to vibrations and shocks.

3.1. QCW Operation of the AOM Tuned QCL

The first demonstration of the AOM tuned QCL [1] was carried out with the laser operating in a quasi-continuous wave mode, with 350 ns pulses at a repetition rate of ~1.3 MHz, corresponding to a duty cycle of 50%. The QCL chip gain was centered at ~9.0 μm and a tunability from ~8.4 μm to ~9.8 μm was demonstrated (Figure 2). Average power as high as350 mW was obtained at the center of the tuning curve (near ~9.2 μm). Such high powers will be needed for standoff detection applications mentioned earlier.

Figure 3 shows the laser frequency tuning as a function of AOM drive frequency, confirming the linear relationship (Eq. 2) within experimental errors.

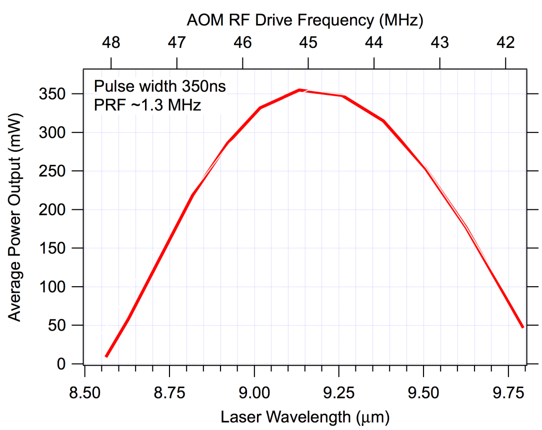

Figure 2. AOM tunable QCL average power output vs. laser wavelength (QCW mode); Top axis shows the AOM drive frequency, which controls the laser wavelength

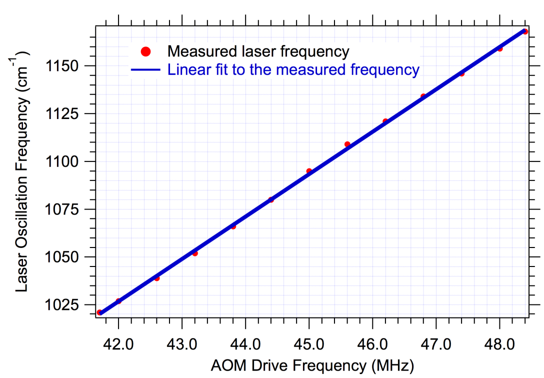

Figure 3. AOM tuned QCL laser frequency as a function of the AOM drive frequency.

Linewidth measurements of the tunable radiation were carried out (Figure 4) to study the effect of AOM drive frequency, by keeping the laser wavelength fixed and changing the AOM drive frequency and simultaneously adjusting the angle θ as required by Eq. (2). Measured linewidth varied from ~3.9 cm^{-1} to ~5.7 cm^{-1} as the AOM drive frequency was changed from 35 MHz to 55 MHz. This variation is understood by taking into account the number of acoustic waves that are intercepted by the optical beam within the AOM crystal [3].

3.2. CW Operation of the AOM Tuned QCL

For some applications, it is important to have the QCL operate in a continuous wave mode rather than the high duty cycle pulsed (quasi continuous wave) mode. The QCW mode ultimately limits the scan speed since the minimum time for switching wavelengths is limited by the pulse repetition rate of the QCW operation. Furthermore, in QCW operation the linewidth is substantially wider than the expected linewidth of ~1.3 cm^{-1} [2]. To confirm the narrower linewidth capability of the AOM tuned QC laser, we operated the system in a CW mode. The observed tuning characteristics of the system (using the same QCL chip as that described earlier for the QCW operation), are shown in Figure 4. The measured linewidth of ~1.7 cm^{-1}, shown in Figure 5, is in reasonable agreement with calculations.

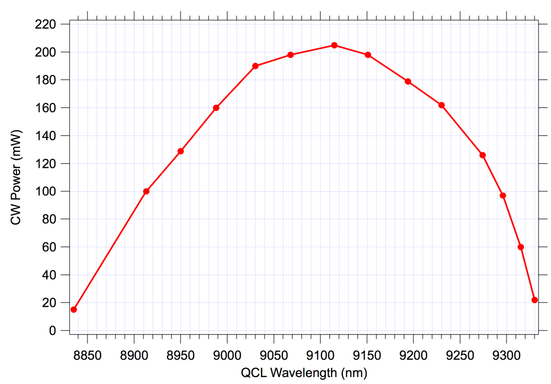

Figure 4. AOM tuning in CW mode (AOM frequency is shown on the top axis)

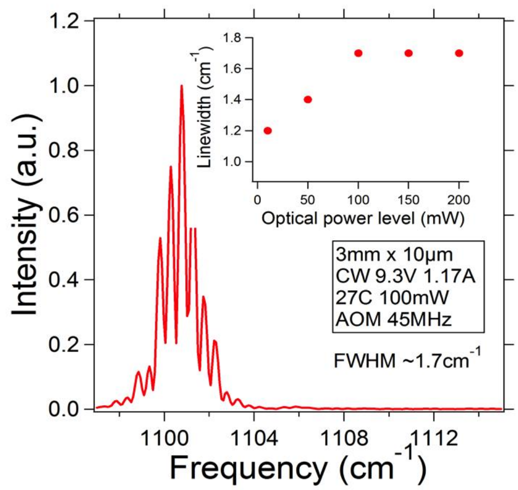

Figure 5. Emission linewidth of CW AOM tuned QCL.

3.3. Wavelength Switching Speed

The ultimate wavelength switching speed is limited by the acoustic transit time through the optical beam traversing the AOM and the speed with which the acoustic frequency can be changed. With AOM frequency in the 30MHz-50MHz, range, the speed of change of frequency is determined by the bandwidth of the AOM frequency generator and amplifier, which in this case is ~20 ns. On the other hand, the acoustic wave takes 700 ns to traverse an optical beam having a diameter of ~4 mm. Thus, the acoustic wave traversal time dominates.

Figure 6 shows measurements of the switching speed. Initially, the AOM frequency is set at 35 MHz, which is outside the wavelength of operation the QCL and there is no laser output. At t=0 (Figure 6), the AOM frequency is changed to 45 MHz (corresponding to the maximum power output), which is the center of the tuning curve shown in Figure 2. As seen from Figure 6, there is no

QCL output until the new AOM frequency of 45 MHz reached the area of interaction with the optical beam (Figure 6).

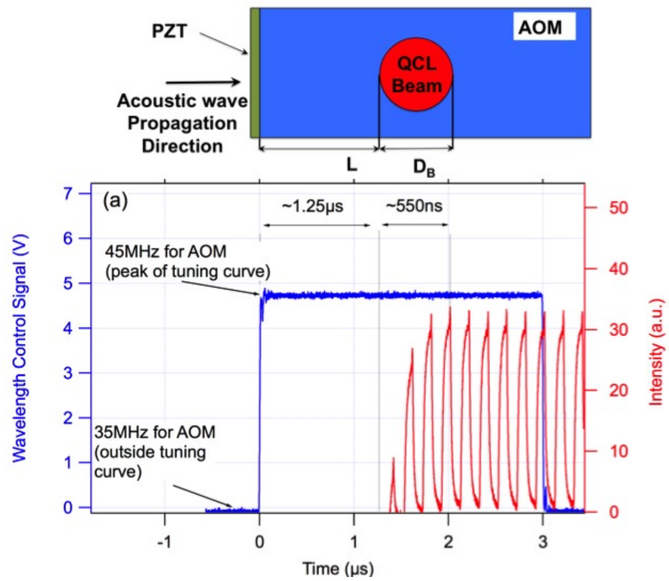

Figure 6. Switching time measurements of AOM tuned QCL. Top panel shows the geometry of the AOM. Panel (a) shows the details of laser turn on when the AOM frequency is changed from 35 MHz (outside the range of AOM tuned QCL operation) to 45 MHz (peak power wavelength for the AOM tuned QCL as seen from either Figure 2 or Figure 4)

The latency period of ~1.25 μm can be shortened to almost zero by moving the optical beam closer to the transducer. However, it should be noted that the latency period is not the true switching time of the AOM tuned QCL. Once the acoustic wave at ~45MHz reaches the laser beam location, the acoustic grating changes the resonant wavelength of the AOM cavity to ~9.1 μm (peak of the AOM tuned QCL output as seen from Figure 2 or 4), and the laser intensity builds up in ~550 ns. This is the true switching time of the AOM tuned QCL. It should be noted that this time is independent of AOM frequency step size, implying that the AOM tuned QCL wavelength can be step changed any one value to another (within the lasing region of the QCL) in ~550 ns.

4. Single Shot Transmission Measurements

In initial experiments we have demonstrated absorption measurements in <19 μs covering a wavelength scan of >1500 nm (Figure 7).

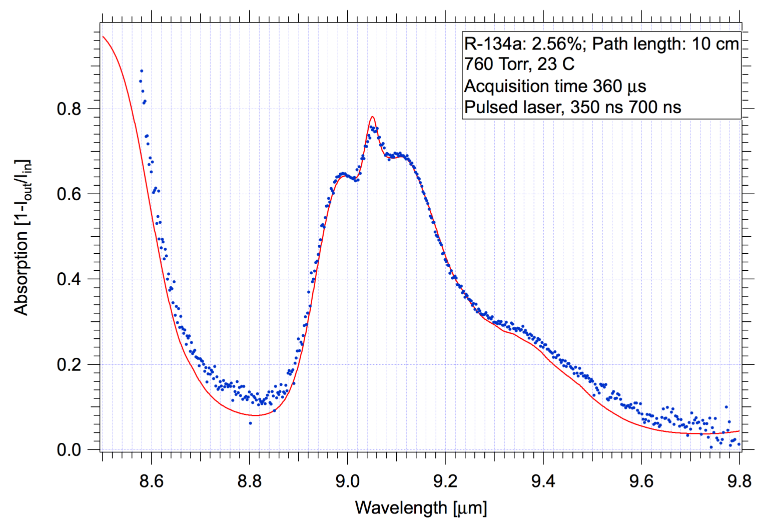

Figure 7. Single shot (17 µs total scan time) transmission data for Freon 134a. HITRAN data were convolved with the measured linewidth of the laser emission (Freon at 2.36% concentration, temperature of 23˚C, and pressure of 760 Torr).

The scan time is limited by the response time of the infrared detectors used in the demonstration. It is clear that the rapid switching and scanning capability opens up applications that are not accessible using traditional grating tuned QCLs.

5. Single shot Standoff Detection

Among many applications of the AOM tuned QCL is the standoff detection from a moving platform such as a vehicle on a rough terrain, identifying IEDs (improvised explosive devices) from safe distances. As mentioned earlier in Section 2, single snapshot type detection is necessary in order to save lives. We have carried out preliminary studies of the suitability of the AOM tuned QCL for this task.

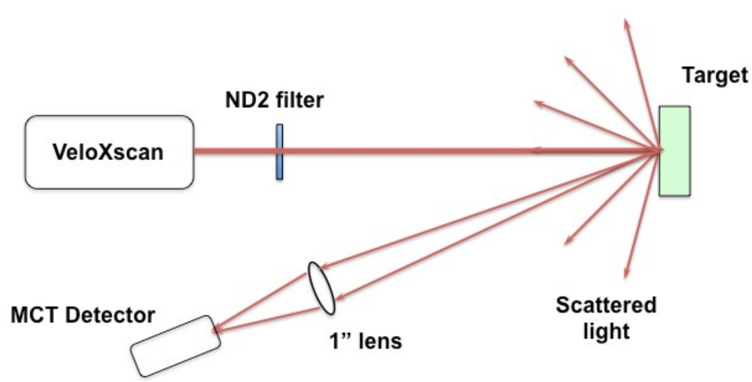

Figure 8. Experimental setup for standoff detection demonstration.

For initial studies, we set up laboratory bench experiment shown in Figure 8. The AOM tuned QCL (packaged as VeloXscan) provided rapidly tunable laser radiation, which is directed towards a target located at ~50 cm from the laser. Laser output is collimated in a beam of ~6 mm diameter and a divergence of ~5 mrad and is not focused further. The scattered light from the target is collected with a 1” diameter 50 mm focal length lens placed at ~25 cm from the target and is received by a MCT detector. The detector output is plotted as the wavelength of the AOM tuned QCL is rapidly scanned form ~8.5 μm to ~9.8 μm.

Three target substances examined were dextrose tablet; dextrose tablet dissolved in water, deposited in an aluminum blank and then dried; and aspirin dissolved in water, deposited on aluminum blank and then dried. The laser output was attenuated using a ND2 filter to prevent the detector from being saturated. Standoff detection spectra were collected in a single 1 ms scan for each of the three samples and measured absorption is shown in Figures 9, 10 and 11 for the dextrose tablet, dissolved dextrose and dissolved aspirin, respectively.

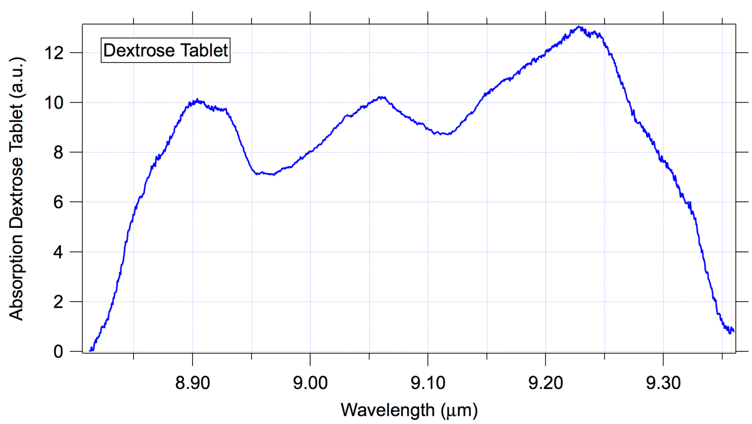

Figure 9. Single shot (1 ms total scan time) standoff detection of dextrose tablet.

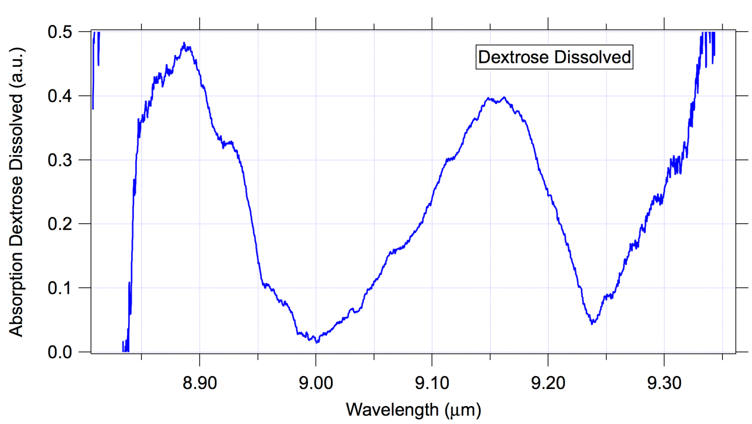

Figure 10. Single shot (1 ms total scan time) standoff detection of dissolved dextrose.

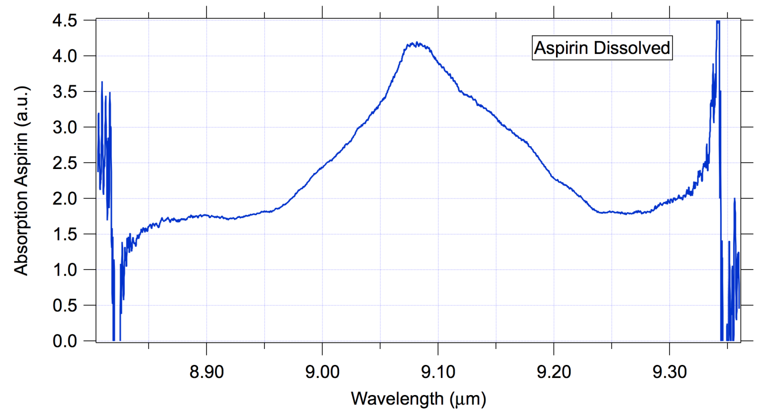

Figure 11. Single shot (1 ms total scan time) standoff detection of aspirin.

It is clear from these preliminary measurements that the three can be identified unambiguously in a one ms scan time. To put the time in perspective, for the example of a vehicle moving at 30 km/h, the vehicle will have moved less than 1 mm during the measurement time, leaving the driver ample time to decide whether to stop the vehicle or to proceed.

6. Conclusion

Many spectroscopic applications require measurements of transient or rapidly changing spectra, such as in the study of combustion and explosion dynamics, the latter being very important for understanding and improving explosives. Many other applications require spectral data to be obtained in a finite, short period of time, such as standoff detection of IEDs and other suspicious objects from a platform that may be traveling at highway speeds. The AOM tuned QCL systems, because they have no moving parts, are inherently rugged for applications in vibration prone environments such as when mounted on moving vehicles, aircraft, helicopters and UAVs. The AOM tuned QCL system opens a broad range of applications that were heretofore considered impossible.

7. References

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