Multipurpose terahertz quantum cascade laser based system for industrial, environmental and meteorological applications

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Multipurpose terahertz quantum cascade laser based system for industrial, environmental and meteorological applications

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Abstract. A portable system, based on a pulsed quantum cascade laser (QCL) is developed. The QCL operates at near to ambient temperature in a pulsed mode with relatively long pulse duration in the range of $200 - 500$ ns. The system design is flexible, allowing its use for a number of open path or cell-internal applications. Due to the so called fingerprint spectral region, high haze and turbulence immunity and low beam divergence, this system can be used in various applications. The first group includes environmental monitoring of a number of trace gases as CH_4, NH_3, CO, O_3, CO_2, HNO_3, hydrocarbons and many others. The meteorological applications include measuring the average humidity and temperature. Industrial surveillance control is another important application. Remote measurement of some physical parameters, as temperature or pressure, as well as for interferometric measurements are also possible. Space resolved study of air turbulence even in fog is another promising application. Security, speed control, open path data transfer and remote readout of information are but a few other real applications of our QCL based portable system.

1. Introduction

Numerical models used in air pollution studies provide a space- and time-averaged description of the atmosphere. Since these models have a typical spatial resolution of 1-5 km for urban areas, running and validating them requires input data of similar resolution [1-3]. Point measurements cannot represent accurately a large spatial area for this purpose, particularly in a poorly mixed atmosphere [4]. Optical remote sensing techniques, such as DOAS and FTIR can directly provide accurate, simultaneous measurements of the average concentration of a number of trace gases over long open paths. However, DOAS measurements are limited to a few compounds absorbing in the UV-visible spectral region. Due to high molecular absorption, the operational range of commercial DOAS systems rarely exceeds 2 km and their measuring abilities are further reduced in aerosol-rich (i.e. smoggy) environments.

Mid-infrared absorption spectroscopy is widely used for monitoring trace atmospheric species. This spectral region is attractive for direct detection in the open atmosphere because of its potentially high sensitivity and selectivity, as well as its intrinsic high immunity against aerosol influence.

The advance of quantum-cascade lasers (QCL) [5] allows the application of a tunable, compact, non-cryogenic source for real-time spectroscopic monitoring of molecular species in the mid-IR. The high optical power and good beam quality of these lasers make them preferable sources for long open-path monitoring systems.

The spatial resolution of open-path measurements can be adapted to the resolution of numerical models [1-3]. Nevertheless, when operating in the open air, a number of complications arise from pressure-induced line-broadening and from atmospheric turbulence. The line-broadening reduces the line contrast, and hence the sensitivity of the measurement and imposes requirements for a broader laser tuning range. The lower sensitivity can be compensated, to some extent, by increasing the optical path-length. However, the maximum path-length is in turn limited significantly by atmospheric attenuation and turbulence. The high optical power of QCLs makes them suitable mid-IR sources for long trajectory open-path monitoring, and, therefore, attenuation over distances of several kilometers is no longer a serious problem. Atmospheric turbulence causes random amplitude variations of the detected signal. These variations induce significant measurement errors when the time for scanning a spectral line is longer than, or comparable with, the characteristic time of turbulent processes (more than 0.3 ms). The most important turbulence-induced effects can be removed if the scanning time is of the order of hundreds of microseconds or less. The individual fast scans are then averaged to minimize the random noise.

Fast wavelength tuning can be realized by driving the laser with "long" (hundreds of nanoseconds) current pulses [6, 7]. The tuning is a result of the self-heating of the laser active media during the pulse (thermal chirp). Tuning ranges of up to 2.5 cm^{-1} and tuning times of the order of 200-500 ns can be achieved by this technique.

In this paper, we report on the design of a portable QCL based system suitable for a number of open-path and cell applications.

2. System design and performance

The system contains several modules. The transmitting module incorporates a QCL, a QCL pulse driver and electronics, collimating optics and a green tracing laser producing a visible beam coaxial to the IR beam. The main parts of the receiving module are a receiving Newtonian telescope, a MCT IR detector and an acquisition system. These two main modules can be configured in a mono-static setup, when the transmitter and the receiver are on the same side of the optical path of interest, or in a bi-static setup when the transmitter and the receiver are on the opposite sides of the optical path. The mono-static setup is more convenient when spatially-resolved measurements are performed; we used this setup in our experiments. The integral view of the system, configured in a mono-static setup, is shown in figure 1.

A simplified block-diagram of the system for spatial resolved measurements is illustrated in figure 2. It contains a transmitter and a receiver and a few "shadow-less" retroreflectors with different sizes. Retroreflectors with equal sizes also can be used but in this case the optical alignment of the system is more complicated. Using the "shadow-less" retroreflectors is important to minimize the signal loses caused by parasitic overshadow from retroreflector walls and holders.

The spatial resolution L at mono-static setup depends on the pulse length as follows: $L=2c/t$, where c is the speed of the light and t is the pulse duration. The maximum distance is limited by the repetition rate of the pulses: $L=2c/T$, where T is the period of the laser pulses. The requirements for better spatial resolution and wider wavelength sweeping are contradictory. Nevertheless, using a pulse duration of about 300 ns allows us to cover a spectral range of about 0.15% (1.5 cm^{-1} @ 1032 cm^{-1}) and to obtain spatial resolution of less than 50 m (45 m @ 300 ns). This tuning range permits us to scan a few

Figure 1. The portable QCL based system configured in a mono-static setup.

absorption lines. If only atmospheric turbulence is studied, a much shorter pulses can be produced. The pulse duration can be decreased down to 10 ns, allowing spatial resolution of 1.5 m.
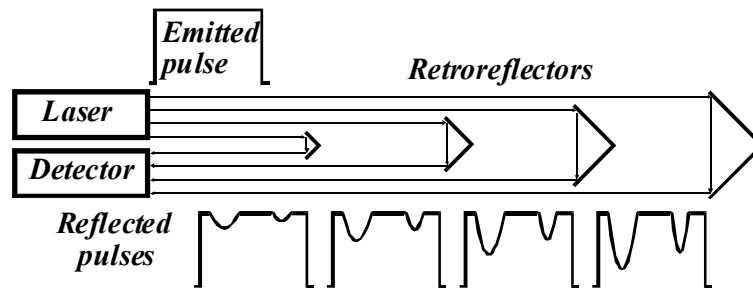
Figure 2. Layout of the experimental setup for spatial resolved open-path atmospheric measurements using pulsed QCL.

3. Applications

Figure 3 shows an example of spatially-resolved water vapor measurements using two retroreflectors. The closer retroreflector has an aperture of 15 mm and is placed at 220 m from the transmitter-receiver station. The farther retroreflector, placed at 2900 m, is 75 mm large. The bottom (purple) curve in figure 3 represents the real signal reflected from both retroreflectors. The left pulse, colored in blue, represents the signal reflected from the closer reflector, while right one, yellow, the signal coming from the farther reflector. Both pulses are shown in corresponding colours "zoomed in" in the upper path of this figure. To improve the signal to noise ratio (S/N), a number of received pulses are averaged. This number depends on the amplitude of the received signal and the precision required and varies between 10 and 100000. Our acquisition system allows the averaging of up to 1000 pulses per second; therefore, the averaging time varies between 0.01 and 100 s. This time interval defines the time resolution of our system.
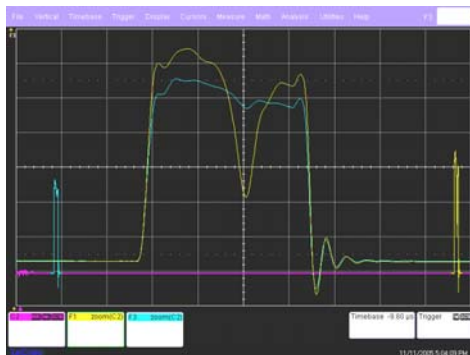

Figure 3. Real signal using two retroreflectors with different sizes placed at 220 m and 2900 m from the transceiver.

When it necessary to measure simultaneously absorbance and air turbulence, one must use pulse averaging to obtain a better S/N ratio and, in the same time interval, use every pulse to characterize fast turbulence. This possibility is illustrated in figure 4 and 5. The improvement of the S/N ratio after
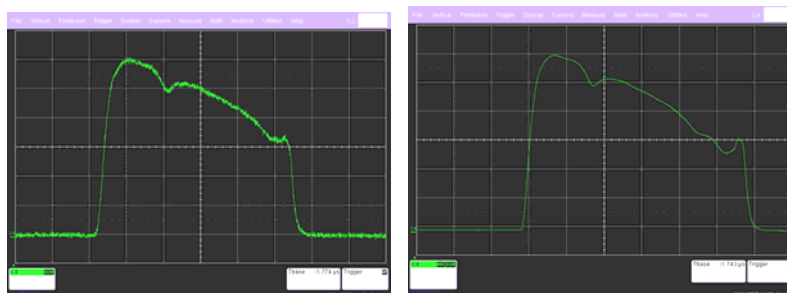

Figure 4. Single shot spectrum taken in 440 m. Open (left) and averaged spectrum (right) obtained from averaging of 1000 spectra.
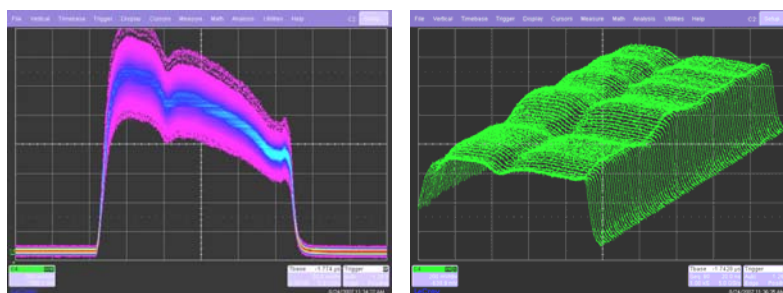
Figure 5. Multiple spectra shown in a persistent mode (left) and a time sequence mode (right).

averaging is obvious from the right-hand part of figure 4 as compared to the left-hand one. Figure 5 shows the amplitude changes of the received pulses caused by the atmospheric turbulence presented in "analog persistent" and "time sequence" modes. The repetition rate in this case is 1 kHz.

Successful experiments were carried out to demonstrate the possibility to detect atmospheric turbulence with a space resolution of 15 m. Four equal corner cube retroreflectors were placed at almost uniform distances to the QCL transmitter – receiver. Figure 6 shows the case when a stronger turbulence is introduced between the third and fourth retroreflectors (at the last part of the path). In this case the fluctuations of the signal corresponding to the reflection coming from the forth retroreflector is much stronger compared to the other three signals.
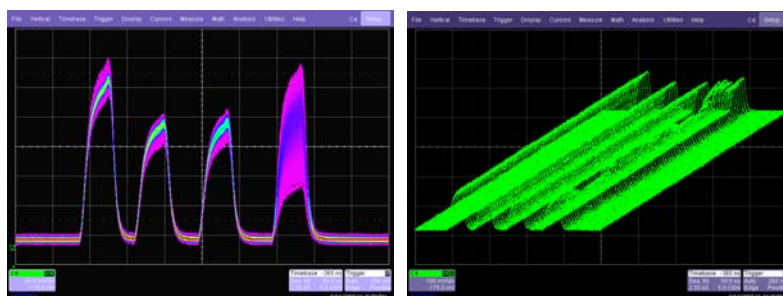

Figure 6. The four reflected pulses in the case of non-homogenous atmosphere.

These spatially-resolved turbulence measurements are promising for initial detection of a fire and for localization of this event with a space resolution of 15 m or better. Another application can be space resolved IR scintillometer operating even in fog and aerosol rich conditions.

4. Conclusion
We report on a portable QCL based multipurpose system applicable for air pollution monitoring, air temperature and humidity measurements, air turbulence spatially-resolved studies, industrial surveillance in closed or open areas and number of other promising applications. The experimental results show excellent sensitivity and selectivity and very good spatial resolution. This system can be used for in-situ plasma spectroscopy as well as for interferometric thickness control of relatively thick films that are opaque in the visible but transparent in MID IR.

Acknowledgements

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