

# Cavity ring down spectroscopy: detection of trace amounts of substance

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*We describe several applications of cavity ring-down spectroscopy (CRDS) for trace matter detection. NO<sub>2</sub> sensor was constructed in our team using this technique and blue-violet lasers (395–440 nm). Its sensitivity is better than single ppb. CRDS at 627 nm was used for detection of NO<sub>3</sub>. Successful monitoring of N<sub>2</sub>O in air requires high precision mid-infrared spectroscopy. These sensors might be used for atmospheric purity monitoring as well as for explosives detection. Here, the spectroscopy on sharp vibronic molecular resonances is performed. Therefore the single mode lasers which can be tuned to selected molecular lines are used. Similarly, the spectroscopy at 936 nm was used for sensitive water vapour detection. The opportunity of construction of H<sub>2</sub>O sensor reaching the sensitivity about 10 ppb is also discussed.*

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**Keywords:** trace matter detection, absorption spectroscopy, laser spectroscopy.

## 1. Introduction

Trace matter detection plays important role for natural science as well as for industry, medicine, environment monitoring, etc. Many physical, chemical and biological techniques were elaborated for this purpose, but each of them is affected by complications and limitations caused by sample preparation or the measuring procedure. Therefore there is a large necessity of novel methods. Promising opportunities are provided by contemporary laser spectroscopy.

Analysis of light absorption spectra in samples is a common method of trace matter detection. In many cases it offers good selectivity. The difficulties, which occur at weak absorption measurement, limit sensitivity of the detection. The extreme sensitivities of low absorption determination are achieved with cavity ring-down spectroscopy (CRDS). In these techniques, the light pulse is trapped inside an optical resonator of a very high quality ( $Q$ ). When the wavelength of radiation coincides with the absorption line of substance filling the resonator, the quality factor decreases. Therefore, the absorption coefficient can be calculated from measurements of the  $Q$ -factor. Sensitivity of  $10^{-9} \text{ m}^{-1}$  is available.

Initially, this technique was used for measurement of reflectivity of mirrors composing the resonator [1]. Then, O’Keefe and Deacon applied CDRS for spectrometry [2]. Within next years, this method becomes a powerful tool with various applications. These achievements were already a matter of reviews books [3,4].

$Q$ -factor determination can be done by several ways. One of them (so-called temporal method) exploits the mea-

surement of the decay time constant ( $\tau$ ) of radiation, which is trapped in the resonator. Let us assume that light injected to the cavity excites the main transversal mode and after the time  $t_0$  the injecting beam is switched off. After it, the radiation intensity inside the resonator decreases exponentially

$$I(t) = I_0 \exp\left(-\frac{t-t_0}{\tau}\right), \quad (1)$$

and the decay time is expressed by

$$\tau = \frac{L}{c(1-R+\alpha L)}. \quad (2)$$

where  $L$  denotes the distance of the mirrors composing the resonator while  $R$  is their reflectivity,  $\alpha$  is the extinction coefficient of the substance filling the cavity while  $c$  is the light speed. We assume that the resonator losses are caused by absorption and the light leakage through each mirror, so they are expressed by  $1-R+\alpha L$  for a single trip of the resonator. The losses cause broadening of the cavity resonance line, therefore the width  $\Delta\omega$  of the angular frequency ( $\omega$ ) band is equal to  $\Delta\omega = 1/\tau$  where  $\nu = \omega/2\pi$  denotes the light frequency. Then, according to definition of the oscillator  $Q$  factor is

$$Q = \frac{\omega}{\Delta\omega} = \omega\tau. \quad (3)$$

The other, so called, phase method of  $Q$ -factor determination is used for amplitude modulated cw laser light (Fig. 1). The technique is based on measurement of the phase shift  $\phi$  between the first harmonics of input and output signals. The shift occurs due to radiation storage in the cav-

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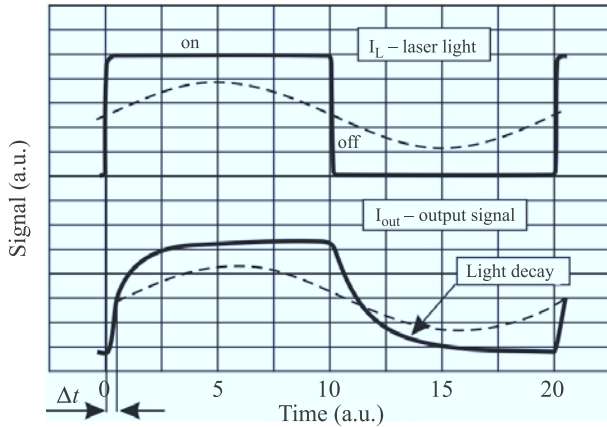


Fig. 1. Input and output signals (solid lines) in CRDS experiment in case of AM laser excitation.  $\Delta t$  is the delay between first harmonics (dashed lines) of these signals.

ity. The value of  $\varphi = 2\pi f\Delta t$  is related to the cavity decay time  $\tau$  by the formula

$$tg(\varphi) = 2\pi f\tau, \quad (4)$$

where  $f$  denotes the modulation frequency. Then, according to Eq. (3), the resonator quality factor is equal

$$Q = \omega \frac{tg(\varphi)}{2\pi f}. \quad (5)$$

The method was introduced by Herbelin [5]. The phase shift can be measured using a lock-in amplifier.

The extinction coefficient can be found by comparing the quality factor (denoted by index “0”) characterizing empty resonator and the quality of the resonator filled with the absorber (no index), respectively

$$\alpha = \frac{\omega}{c} \left( \frac{1}{Q} - \frac{1}{Q_0} \right) = \frac{2\pi}{\alpha} \left( \frac{1}{Q} - \frac{1}{Q_0} \right). \quad (6)$$

Combining Eqs. (1–5) and substituting them to Eq. (6) one find that

$$\alpha = \frac{1}{c} \left( \frac{1}{\tau} - \frac{1}{\tau_0} \right) = \frac{2\pi f}{c} [ctg(\varphi) - ctg(\varphi_0)]. \quad (7)$$

for temporal, and phase method, respectively. Equation (7) provides opportunity to determine the minimal absorber concentration, which can be determined with CRDS method

$$C_{LMT} = \frac{(1-R)}{\sigma L} \frac{\Delta\tau}{\tau_0} \approx \frac{2\pi f(1-R)}{\sigma L} \frac{\Delta\varphi}{tg(\varphi_0)}, \quad (8)$$

where  $\sigma$  denotes the absorption cross section while  $\Delta\tau$  and  $\Delta\varphi$  are the temporal or phase shift resolution of the measuring system.

Optical cavity can effectively store the radiation only when it is well adjusted to the cavity modes. Matching the cavity modes to laser frequency is often done with control of position of one mirror with piezo-element involved in feedback loop with output light intensity detector. Engeln *et*

*al.* presented modification of CRDS technique which provides opportunity to avoid this complication [5]. It is based on off-axis arrangement of the resonator (Fig. 2). In this configuration, the light is repeatedly reflected by the mirrors (like in multipass cells, Ref. 6), however, the reflection points are spatially separated. The free-spectral range (FSR) of an off-axis cavity can be  $n$  times less than the FSR of an on-axis aligned cavity, where  $n$  is the number of the round trips for which a ray returns exactly to its entrance point. Due to that, either the dense mode structure of low finesse occurs or the mode structure does not establish at all. Avoiding light interference, it allows us to eliminate sharp resonances of the cavity, so the problems connected with their coincidence with laser modes and sharp absorption lines do not occur.

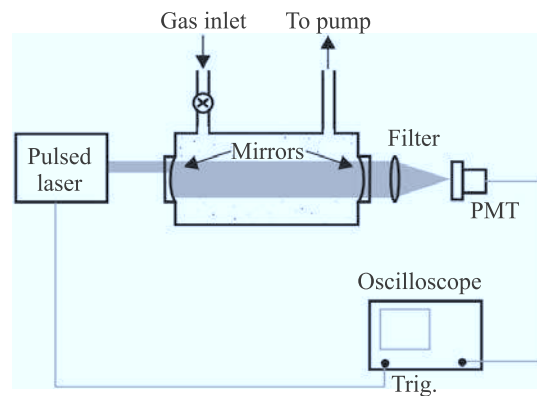


Fig. 2. Principles of experimental setup for off-axis CRDS.

The off-axis design eliminates also the optical feedback from the cavity to the light source. This is especially important when diode lasers are applied. Moreover, in these configurations, the light is many times reflected by the mirrors and it fills the whole volume of the cavity. In comparison with ordinary CDRS, off-axis cavity adjusting is much less sensitive for the cavity misalignment caused, e.g., by the refractive index fluctuations due to turbulences or small mechanical instabilities.

We applied the off-axis arrangement with pulsed diode laser for detection of trace gases in the atmosphere.

## 2. Detection at electronic molecular transitions

Nitrogen oxides belong to common atmospheric components. Amount of  $\text{NO}_x$  in the air is one of the main factors of atmosphere purity. Their monitoring is also useful for combustion processes control, for the explosives detection, for medical applications, etc. In free air, the nitrogen oxides occur mainly as a mixture of stable  $\text{NO}_2$ , its dimmer  $\text{N}_2\text{O}_4$ , as well as  $\text{N}_2\text{O}$  and  $\text{NO}$  molecules. Their reactions with  $\text{H}_2\text{O}$  lead to acid rains. Atmospheric photochemistry induces a complicated mechanism of conversion between nitrogen oxides [7]. Due to these processes, as well as due to natural biochemistry, a small amounts of unstable  $\text{NO}_3$  and  $\text{N}_2\text{O}_5$  molecules occur as well [8].

## 2.1. NO<sub>2</sub> sensor

A lot of papers were dedicated to optical detection of nitrogen dioxide. As it was shown in Fig. 3, the absorption spectrum of this compound has a band in 395–430 nm range with a mean cross section of  $6 \times 10^{-19} \text{ cm}^2$  ( $\pm 30\%$ ). It corresponds to  ${}^2A_1 - {}^2B_1$  and  ${}^2A_1 - {}^2B_2$  electronic transition. First labsetups of fully optoelectronic sensor of NO<sub>2</sub> using CRDS methods have been demonstrated already [9–15]. Various light sources are applied for this purpose: blue – violet LED's or diode lasers or even the broadband supercontinuum sources [16–18]. For laboratory systems, the sensitivities reaching 100 ppt were reported [17–20].

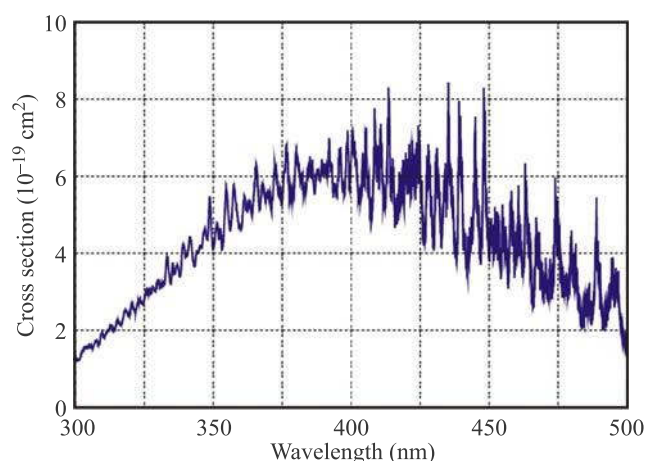


Fig. 3. NO<sub>2</sub> absorption spectrum. Arrows show the emission range of various blue-violet diode lasers.

Our approaches to nitrogen dioxide detector were already described in several papers [19–21]. Here, we present properties of our recently elaborated compact optoelectronic NO<sub>2</sub> sensor.

Cross section of the sensor is presented in Fig. 4. It consists of a chamber that is fixed to the optical plate. The tube of the optical cavity is composed in a volume between the housing and the side cover. The cavity is constituted by two mirrors (Los Gatos) which reflectivity is better than 0.9999 at the wavelengths of  $410 \pm 15 \text{ nm}$ . Their radius of curvature is 1 m while the distance between them is 37 cm. The mirrors are mounted in two hermetic gimbals which are fixed to frontal surfaces of the chamber. The holders seal up the mirrors to the chamber and ensure precise regulation of their tilt over the angle of  $\pm 3^\circ$  in respect to the cavity axis.

The investigated air enters to the cavity tube perpendicularly to the light beam through the inlet located in the top cover and leaves the chamber through six outlets located on the side of its housing. Fans fixed at the outlets stimulate the air flow. Volumes between the top cover and the down cover are used for filter papers which eliminate aerosol from the investigated air and protect the cavity mirrors against contamination by dust.

All metal elements of the chamber are made of duralumin. In order to reduce the gas adsorption on the walls

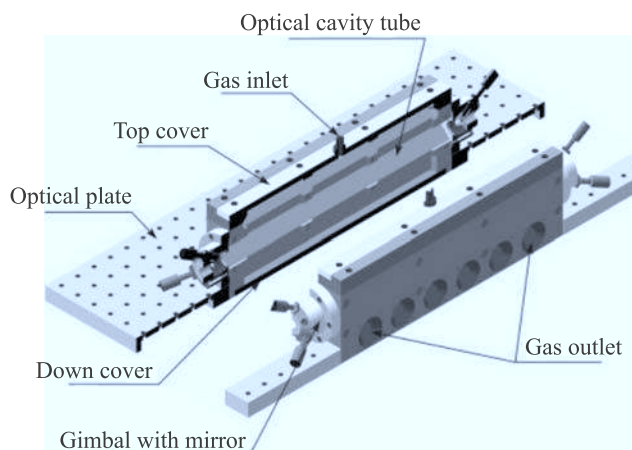


Fig. 4. Cross section of NO<sub>2</sub> sensor mechanical construction.

(which might lead to large experimental errors when a low NO<sub>2</sub> concentration is investigated), the surfaces of all elements were coated with 0.3-mm layer of teflon. Adhering surfaces of the parts were sealed up with O-rings. The covers were fixed to the housing with screws.

Such construction of the optical sensor is very stable. A proper adjustment of the cavity was not spoiled within several months. Despite the sensor was subjected to displacements and vibrations, no correction was necessary. Due to good air filtering, no mirrors' cleaning was necessary as well, although the cavity was used in dusty air. However, in order to protect the mirrors against the moisture deposition their temperature should be kept at  $\sim 40^\circ\text{C}$ . This is done by electric heating of mirror holders.

NO<sub>2</sub> sensor was tested in a setup that is shown in Fig. 5. Pulsed violet diode laser (TopGaN) working at 407 nm was applied. Parameters of laser pulses were: 100 ns FWHM duration time, 200 mW peak power, and 1 kHz repetition rate. The laser light illuminated a blazed grating ( $2400 \text{ mm}^{-1}$ ). The beam reflected at zero-order was directed to a photodiode to produce the reference signal. The beam deflected at first order passed through an iris diaphragm and illuminated the cavity. Use of the grating and the diaphragm reduced the broadband amplified spontaneous emission and fluorescence from a laser diode. Spectrum of this emission is much broader than the width of a high reflectivity band of the mirrors. Without such filtering, the fluorescence light can leak through the cavity and then reaching the photodetector it can strongly affect the experimental signal.

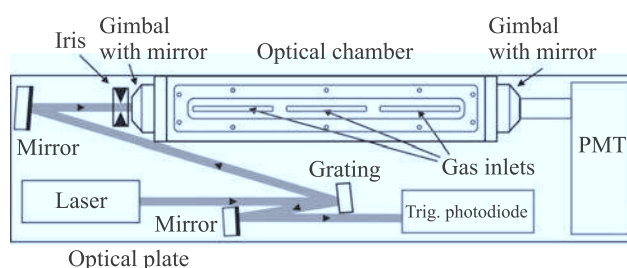


Fig. 5. Experimental setup of NO<sub>2</sub> sensor.

Test of the sensor was performed with a controlled air – NO<sub>2</sub> mixture. The temporal determination of the  $Q$  factor was applied. In order to ensure a good signal-to-noise ratio, the registration was averaged over 40 thousand of laser pulses. When no absorber was in the resonator, we observed the decay time  $\tau_0 \approx 8 \mu\text{s}$ . Then, the cavity was connected with the gas mixing system supplied from a bottle with NO<sub>2</sub> – air mixture of 50 ppb mixing ratio. The mixture was additionally diluted with pure nitrogen using two gas flow controllers (Beta-Erg), so in this way the mixing ratio of the gas inside the cavity was regulated. In order to avoid disturbing of optical homogeneity of the medium, the gas flow was reduced to about 3 l/min. The output signal was registered with a photomultiplier (R7518, Hamamatsu) equipped with the interference bandpass filter matched to the laser line.

In Fig. 6, we demonstrate the results of our investigations. Good agreement was achieved between the measured absorption coefficients and that one calculated for corresponding NO<sub>2</sub> concentrations when the absorption cross section of  $5 \times 10^{-19} \text{ cm}^2$  is assumed. On the other hand, for the wavelength of the laser (407 nm) value of this cross section is  $5.5 \times 10^{-19} \text{ cm}^2$ . The error can occur not only due to CRDS technique uncertainty but also due to the error of the mixture preparation. Uncertainty of linearity coefficient does not exceed 5%. Sensitivity of single ppb was achieved and it can be increased by application of specialized signal processing system improving the precision of radiation decay time measurement.

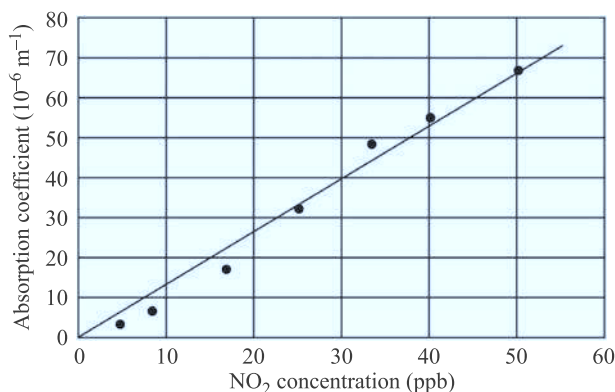


Fig. 6. Measured absorption coefficient of nitrogen dioxide vs. mixing ratio of air-NO<sub>2</sub> mixture.

## 2.2. Experiment with NO<sub>3</sub>

Beside nitrogen dioxide, NO<sub>3</sub><sup>\*</sup> radical plays an important role in atmospheric chemistry, especially in hydrocarbonates oxidation mechanisms [22,23]. Its absorption spectrum is presented in Fig. 7 (continuous line) [24,25]. Maximal cross sections at 662 nm reach relatively large value of  $4.5 \times 10^{-17} \text{ cm}^2$ .

The experiment NO<sub>3</sub><sup>\*</sup> with radical detection was performed in a cavity composed of two mirrors from VIGO ( $R > 99.9\%$ ) which high reflectivity bandpass covered 635–680 nm range. As the light source, the dye laser with rhodamine B pumped by II harmonic of Nd:YAG laser was

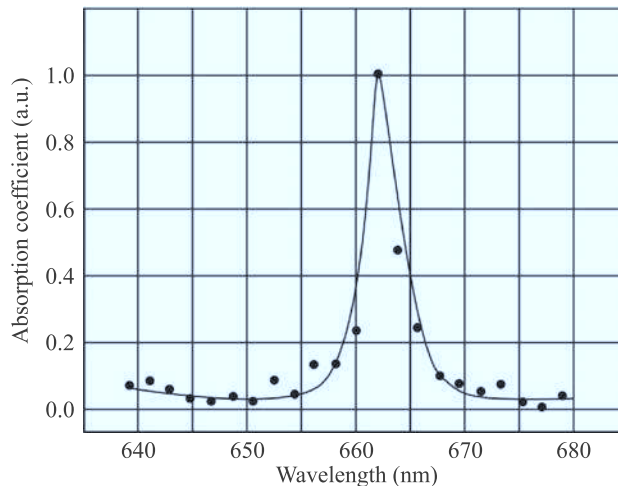


Fig. 7. Absorption spectrum of gases that occurs in air under electric discharge (points) in vicinity of NO<sub>3</sub> absorption peak at 662 nm.

applied. The wavelength was measured with a monochromator calibrated by a sodium lamp. Other optical component of the system was similar as for NO<sub>2</sub> detection.

Nitrogen oxides were produced by electric spark in the air which was initiated a few centimetres before the sensor input. The measured spectrum is presented in Fig. 7 (points). For 662 nm, corresponding to the maximum of NO<sub>3</sub> absorption, the extinction coefficient of  $4.67 \times 10^{-6} \text{ cm}^{-1}$  was observed which corresponds to NO<sub>3</sub> concentration of  $10^{11} \text{ cm}^{-3}$  (about 4 ppb).

One of the most important sources of the experimental errors is ozone which is also produced in the electric discharge. Its absorption cross section in the red region is about  $4 \times 10^{-21} \text{ cm}^2$  [26]. In spite of that, this value is much smaller than NO<sub>3</sub> absorption cross section, in such circumstances O<sub>3</sub> concentration can be several order of magnitude larger than NO<sub>3</sub> concentration. Unfortunately, the ozone sensor was not available in this experiment. Nevertheless, from Fig. 7 one can state that the systematic error caused by O<sub>3</sub> was not larger than 10%.

One can evaluate, that in a system, the minimal NO<sub>3</sub> concentration which was possible for registration was about  $2.5 \times 10^9 \text{ cm}^{-3}$  (ok. 0.1 ppb) when the sensor is not affected by systematic error from ozone. The sensitivity is mainly limited by the precision of photon lifetime measurement  $\Delta\tau$ , Eq. (8). Improvement in the resonator  $Q$ -factor determination (4–7) can be performed over one order of magnitude thanks to replacing the digital oscilloscope by a specialized electronic system. Therefore one can state that with CRDS technique, NO<sub>3</sub> concentration can be measured with ppt – precision.

## 3. Detection at vibronic molecular transitions

Observation of NO<sub>2</sub> and NO<sub>3</sub> molecules was done at electronic transitions which are characterized by broad absorption spectra providing relatively large mean cross section within the range of several nanometers. Therefore applica-

tion of broadband multimode lasers was possible. For many other compounds contained in the air, which monitoring is interesting (like  $\text{H}_2\text{O}$ ,  $\text{N}_2\text{O}$  and  $\text{NO}$ ), the electronic transitions correspond to ultraviolet spectral range below 200 nm [27,28], where neither the suitable laser sources nor the high reflectivity mirrors are available. Therefore the detection of such molecules should be performed at vibronic transitions situated in infrared spectral range.

### 3.1. $\text{H}_2\text{O}$ detection

Our first approach to such detection was done with water vapour in 920–980 nm range.  $\text{H}_2\text{O}$  is a compound that is universally present in the air. Although in the atmosphere at low altitudes water vapour concentration usually reaches several parts per thousand, and it can be measured by common humidity meters, the detection of  $\text{H}_2\text{O}$  at altitudes higher than 10 km requires the sensitivity of single ppb. Such sensitive  $\text{H}_2\text{O}$  measurement is also important for many industrial and scientific applications.

Overtone absorption spectrum of  $\text{H}_2\text{O}$  molecule in the atmosphere in 920–980 nm range is presented in Fig. 8. The spectrum consists of narrow separated lines. The lines are usually shifted and broadened by pressure effects. Parameters of these interactions are collected in standard databases like HITRAN [27] or ESA [28]. That allows the line shapes approaching [29], however, precise determination of their profiles (and the absorption cross section) is still a matter of intensive studies [30–33]. Width of separated lines is of the order of  $0.1 \text{ cm}^{-1}$  ( $\sim 0.01 \text{ nm}$ ). Therefore the spectroscopy of water vapour requires using of narrow line tunable lasers.

Our system of  $\text{H}_2\text{O}$  detection was build with single mode diode laser (Toptica D100) tuned to 935.703 nm ( $10687.15 \text{ cm}^{-1}$ ). For this line, the absorption cross section is about  $4 \times 10^{-21} \text{ cm}^2$ . The laser wavelength was monitored with WaweMaster (Coherent) lambda meter. Continuous light beam was AM modulated by acousto-optic cell (Brimrose).

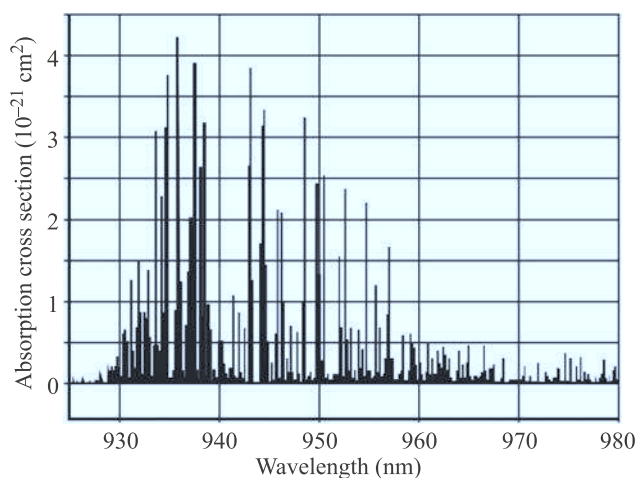


Fig. 8. Absorption spectrum of water vapour in air at normal pressure at reference temperature 296 K.

The investigation was performed in a stainless steel tube of 80-cm length. The tube was terminated with two mirrors of reflectivity of about 0.999 composing the optical resonator. The light leaving the cavity was registered with Hamamatsu R94-02 photomultiplier equipped with low-pass colour glass filter (KS-19). The signal was collected by multiscaling photon counter (ARCO). The temporal method of CRDS signal analysis was applied.

The tube was attached to the vacuum system. The resonator was filled with laboratory air of relative humidity about 25–40% (7–us 12 ppth). The air pressure was controlled using precise valves. It provides regulation of  $\text{H}_2\text{O}$  concentration in the tube. Air pressure was measured with a barratron. Humidity and temperature of the air entering to the system was determined with commonly used instruments. Filtering of the air allowed us to avoid contamination of mirrors by dust and aerosols.

Results of the absorption measurements around  $10687 \text{ cm}^{-1}$  line are presented in Fig. 9. The line is affected by collisional broadening, so its shape can be described by Voigt profile. Changes of collision frequency, when the air pressure decreases, lead to change of the line profile.

The measurements were done with cheap mirrors of low reflectivity ( $R \approx 0.999$ ), therefore the sensitivity of the absorption measurement reached about  $10^{-4} \text{ m}^{-1}$  only. Such absorption corresponds to  $\text{H}_2\text{O}$  concentration of  $10^{14} \text{ cm}^{-3}$ . The absorption coefficient determined in this experiment agrees well with water vapour concentration evaluated from parameters of the air that was introduced to the system. Sensitivity of  $\text{H}_2\text{O}$  detection achieved in this experiment corresponds to concentration of 10 ppm.

It results from Eq. (8) that the sensitivity can be improved about 50 times using better mirrors ( $R = 0.99998$  are available). Another improvement (by a factor of 10) can be achieved using a specialized photoreceiver system due to increase of  $\Delta\tau$  precision again by one order of magnitude, Eq. (8). Moreover, the sensitivity can be increased about 50 times when the measurement will be performed in 1340-nm spectral range where the absorption coefficients of  $\text{H}_2\text{O}$

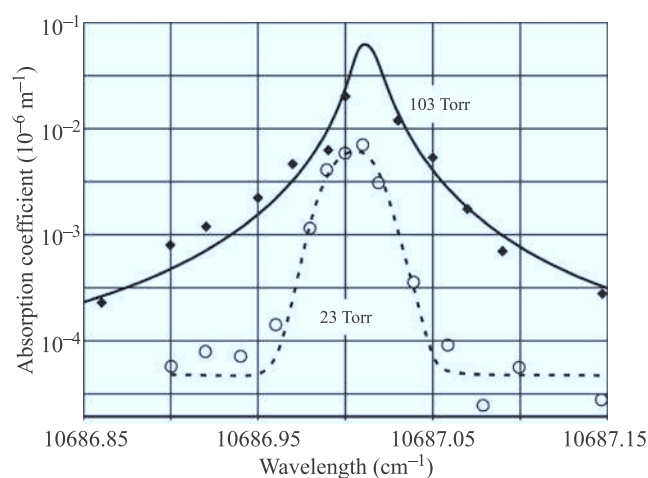


Fig. 9. Selected absorption line of  $\text{H}_2\text{O}$  in air at 130 Torr and at 23 Torr.

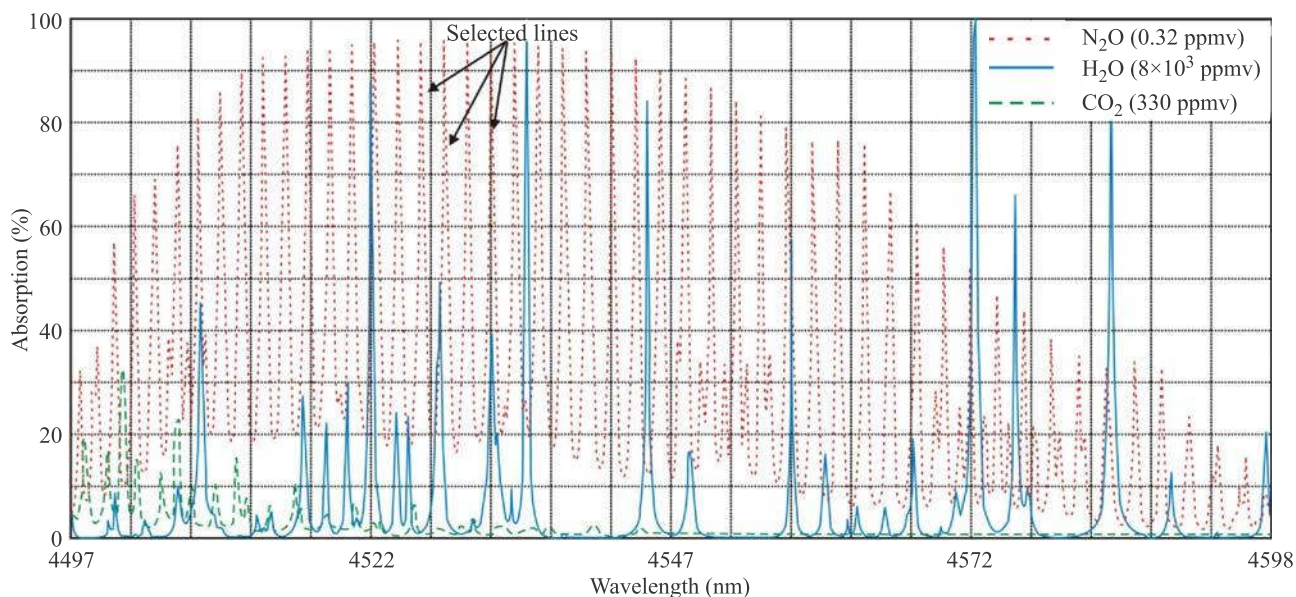


Fig. 10. Absorption spectra of  $\text{N}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{H}_2\text{O}$  in air in 4.49–4.59  $\mu\text{m}$  range.

molecule are much larger. Single mode laser sources and the detectors of high sensitivity are commercially available for these wavelengths.

This raw evaluation shows that with CRDS system the detection of single ppb is possible. While the most sensitive contemporary methods are about two orders of magnitude less sensitive, the construction of water vapour sensor using CRDS technique is an interesting challenge [34].

### 3.2. Experiment with $\text{N}_2\text{O}$

Spectra of  $\text{NO}_2$ ,  $\text{NO}_3$ , and  $\text{H}_2\text{O}$  which were discussed in previous parts of our paper, practically are not interfered by other gases (like  $\text{CO}_2$ ) commonly present in the air. Different situation for  $\text{N}_2\text{O}$  occurs. Its high absorption peaks correspond to 4.45–4.65  $\mu\text{m}$  range, where both  $\text{CO}_2$  and  $\text{H}_2\text{O}$  can strongly affect the measurements. Comparison of these spectra for US Standard Atmosphere 1976<sup>1</sup> was presented in Fig. 10. Avoiding  $\text{CO}_2$  interferences requires the wavelength selection of above 4.5  $\mu\text{m}$ . We have chosen 4.524, 4.526, and 4.53  $\mu\text{m}$  lines of  $\text{N}_2\text{O}$ . This range is weakly affected by  $\text{H}_2\text{O}$  interferences as well.

Our preliminary experiment about  $\text{N}_2\text{O}$  detection by CRDS method was performed with optical parametric oscillator (EKSPLA, model TG711/DSG). The setup is presented in Fig. 11. Parameters of the light pulses were: FWHM duration time about  $\sim 20$  ps, energy – 8.9  $\mu\text{J}$  (at  $\lambda = 4.50$   $\mu\text{m}$ ), repetition rate about 1 kHz. Optical cavity from Los Gatos was used. Reflectivity of the mirrors reached about 0.9999. Highly divergent output beam from parametric oscillator was collimated by germanium lens ( $f = 75$

mm). Next beam was shaped with a diaphragm (1 mm diameter) and it was directed to the cavity. Another lens was used to collect output radiation which was focused on photodetector (PVI-2TE-5, VIGO System S.A). Signal acquisition was performed with a digital oscilloscope (DPO4104, Tektronix).

The linewidth of parametric oscillator is about 0.001  $\mu\text{m}$  so, it overlaps several absorption peaks of  $\text{N}_2\text{O}$ . In vicinity of the investigated lines, the mean value of the absorption cross section reaches about  $6 \times 10^{-19}$   $\text{cm}^2$ . In such circumstances, the registration of 10 ppb was possible.

Aim of this experiment was checking of the experimental setup before using of quantum cascade lasers (QCL). These radiation sources are the most suitable for CRDS experiments in this spectral range. Some models of QCL's manufactured by Alpes provide narrowband pulses of radiation which are well tuned to  $\text{N}_2\text{O}$  lines: 4.5239, 4.5258, and 4.5297  $\mu\text{m}$ . Peak absorption cross section at these wavelengths reaches  $8 \times 10^{-18}$   $\text{cm}^2$ , so essential increase (about one order of magnitude) in the sensitivity might be expected.

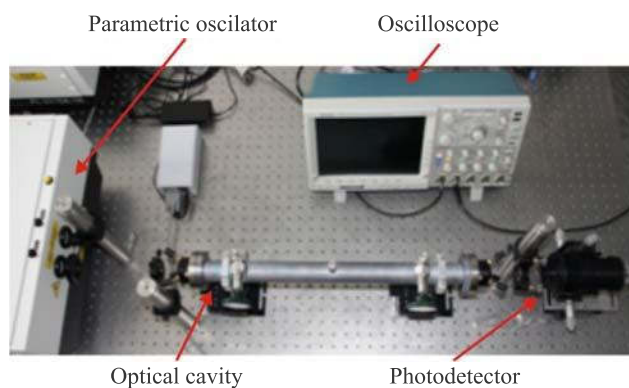


Fig. 11. Experimental setup for  $\text{N}_2\text{O}$  detection.

<sup>1</sup> According to this standard at temperature 300 K and normal pressure  $\text{CO}_2$  concentration is 330 ppm,  $\text{H}_2\text{O}$  – 773 ppm, while  $\text{N}_2\text{O}$  – 0.32 ppm.

## 4. Conclusions

Several experiments with cavity ring – down spectroscopy were performed in order to check usefulness of this method for trace detection of various substances. Good results were achieved with NO<sub>2</sub> using broadband pulsed lasers working in blue-violet range. Successful nitrogen dioxide monitoring (< ppb in air) is possible due to large absorption cross section of this molecule. Detection of H<sub>2</sub>O requires using of single mode tunable lasers, because the spectrum of this molecule in near infrared region consists of narrow separated peaks. However, due to that, the method provides opportunity to build H<sub>2</sub>O sensor of sensitivity of single ppb. Detection of N<sub>2</sub>O, which is also done in vibronic transitions, requires using of precisely tunable lasers as well. Careful selection of spectral range is necessary in order to avoid interferences by water vapour and CO<sub>2</sub> which are commonly present in the atmosphere. With QCL, the sensitivity of the order of single of ppb might be achieved. The experiments show that contemporary electronics applied for CRDS provides opportunity to construct fully optoelectronic sensors of trace matter.

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