



DETECTION OF ETHANE, METHANE, FORMALDEHYDE AND WATER VAPOR IN THE 3.33 μm RANGE

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Abstract

We describe construction and investigation results of optical trace gas sensor working in the 3.334–3.337 μm spectral range. Laser spectroscopy was performed with a multipass cell. A setup was elaborated for detection of ethane at the 3.3368035 μm absorption line. Analysis of the gas spectra and the experiment have shown that, beside C_2H_6 , the sensor is suitable for simultaneous detection of methane, formaldehyde and water vapor. Due to nonlinearity of the laser power characteristic we decided to detect the fourth harmonic of signal. Additional laser wavelength modulation was applied for optical interference suppression. In result, the precision of ethane detection of approximately 80 ppt has been achieved for the averaging time of 20 seconds. Long-term stability as well as the measurement linearity have also been positively tested. The system is suitable for detecting potential biomarkers directly in human breath.

Keywords: infrared spectroscopy, multipass, biomarkers, trace gas sensing.

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1. Introduction

Detection of trace gases is important for many human activities: from monitoring of industrial processes [1] and investigation of their environmental impact [2] to medical diagnostics of various diseases by measurement of biomarker concentration in exhaled breath [3,4]. Therefore, searching for novel methods of trace gases determination is desirable. Biomarkers are the compounds in breath that provide information about health and help monitoring wellness. Noninvasive, painless and real-time measurements (~ 1 min) are the main advantages of breath investigation compared to other existing diagnostic procedures.

There is a growing interest in the detection of ethane (C_2H_6) in breath. This colorless, odorless gas is an inflammatory marker in the exhaled air. It might be also used as an indicator of vitamin E deficiency [5], as well as for identification of chronic respiratory diseases [6], oxidative stress [7], scleroderma [8] and cystic fibrosis [9, 10]. Exhaled ethane is an *in vivo* biomarker of lipid peroxidation in interstitial lung diseases [11–13], schizophrenia [14–16], diabetes, and

asthma [17]. Moreover, breath ethane peaks during a single hemodialysis session and is associated with dialysis time [18]. Ethane is thus an excellent indicator of oxidation stress and its presence in breath could offer non-invasive, dynamic assessment of ongoing cell damage.

The majority of clinical studies involving ethane have been conducted using non-real-time techniques such as gas chromatography coupled with mass spectroscopy or other detection methods. These studies found that C_2H_6 concentration in normal human breath is about 0.12 ppb, while in the case of a disease it may reach several ppb [19]. Although improved methods of gas chromatography have been developed [20], the real potential of ethane detection in medical diagnosis has been hampered by the absence of real-time technology of sufficient sensitivity. Novel type of breath analyzers, which may be developed due to progress in laser spectroscopy and optoelectronics, could be inexpensive, selective, sensitive and simple in maintenance.

Several optical solutions employing the spectral range around 3.3 μm have already been presented. High sensitivity and measurement precision of 70 ppt was achieved in a portable system for analysis of ethane in exhaled breath using multipass absorption spectroscopy [21]. The detection limit of 270 ppt in the system with optical cavity (CRDS) was presented as well [22]. Optical systems have been also reported in clinical applications [23–25].

2. Experimental

For high sensitivity optical identification of trace gases, a strong absorption line of the compound of interest must be chosen. One has also to avoid the disturbance of this line by other species which might be present in the investigated sample. This is especially important in the case of breath analysis as more than 3000 various constituents have already been detected in exhaled air. Ethane band consisting of 9 strong lines is located within the 3.3325–3.3630 μm range [26]. We selected the 3.3368 μm line for detection of this compound. Although it is not the strongest peak in the ethane spectrum, we found that it is the least interfered.

Water vapor, methane and formaldehyde are the main compounds whose spectra may overlap the C_2H_6 line. At atmospheric pressure of 1013 hPa, the line shapes are mainly determined by the effect of collisional broadening [27]. Broad spectra of H_2O , CH_4 and H_2CO hamper the high sensitivity of ethane observation (Fig. 1a). Lowering of sample air pressure to 101.3 hPa efficiently reduces this broadening and leads to line separation (Fig. 1b). The absorption peak of C_2H_6 (3.3368035 μm) is much less interfered with. Therefore, the detection of the ethane with the sensitivity below 1 ppb should be possible.

The basic system (so called single pass spectroscopy) for detection of gaseous compounds was already described in many optical manuals (for example [27]). It consists in measurement of the light quenching in the sample and applying the Lambert–Beer absorption law. We use the improved method called multipass spectroscopy. The sample cell is placed between two mirrors so that the laser beam passes through the sample multiple times. As a result, the light path might be lengthened tens or even hundreds of times in the sample. Additionally, in order to achieve good selectivity of compound identification the laser light should be precisely tuned to the specific absorption line of the molecule of interest. All these solutions together with the application of a specific laser spectroscopy approach (wavelength modulation–WMS – see Section 3) lead to an increase in both sensitivity and selectivity.

A scheme of our experimental setup is presented in Fig. 2. A Nanoplus ICL 3 mW continuous wave tunable laser was applied as a light source. Its temperature was stabilized at 289 K with a Optica DCT 110 module. Fine tuning of the laser current within 30–70 mA through a Thorlabs TLD001 controller allowed the wavelength change within the 3.334–3.337 μm range. Beside the

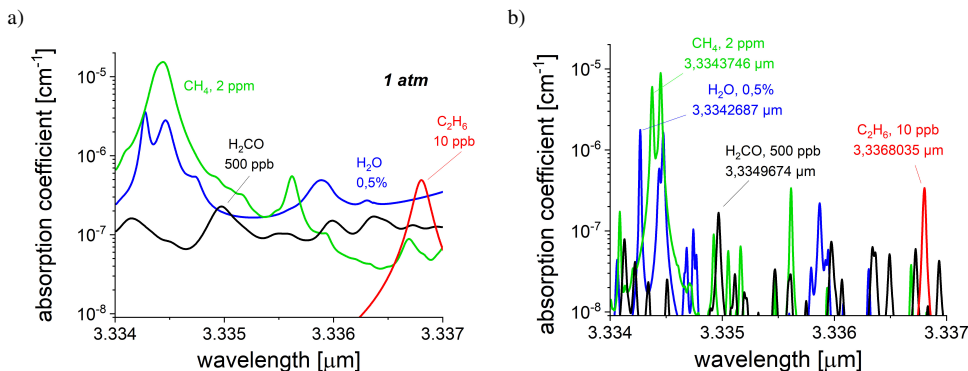


Fig. 1. Absorption spectra of ethane and main interferents occurring in air as calculated from the HITRAN database at pressure of a) 1013 hPa; b) 101.3 hPa.

ethane absorption line (3.3368035 μm), such a broad range contains also strong lines of water vapor, methane and formaldehyde (Fig. 1b). Each of these substances has at least one absorption line with an undisturbed peak and one of the slopes. This allows simultaneous observation of all these constituents with a single detection system.

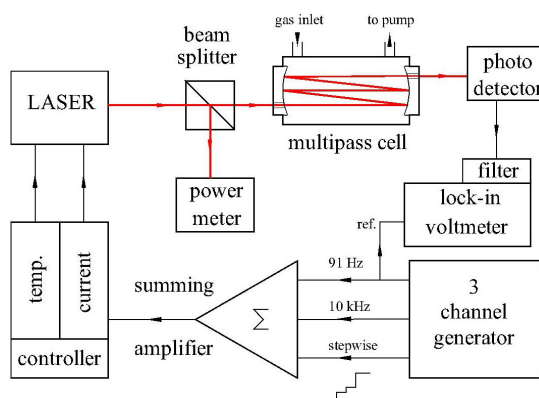


Fig. 2. Scheme of the experimental system.

The laser beam was directed to a beam splitter. The outcoupled ray served for laser power monitoring with a Thorlabs PDA20H PbSe photodetector. The main beam was sent to the measuring cell. A custom Herriot multipass cell characterized by the optical path length of 17.5 m was used in our experiment [28, 29]. The cell was filled with the investigated gas sample. Its pressure was regulated by a vacuum system.

A three-channel generator (a combination of AFG 3102 model from Tektronix and JDS 6600 from JOYIT) was used for the laser tuning. Output signals from the channels were combined in a custom summing amplifier and directed to the current controller. The channel providing a stepwise signal was used for consecutive tuning of the laser to the peaks of selected compounds. For WMS, the laser current was modulated with a sine wave signal (91 Hz) which resulted in modulation of the laser wavelength. Due to presence of the absorption line, this wavelength modulation was transferred into intensity modulation (at 91 Hz and its harmonics) that was

detected with a PbSe photodetector (Thorlabs, PDA20H) and a lock-in amplifier (Stanford SR830) that also enabled extracting the signals at specific harmonics of the modulation frequency. Because the amplitude of resulting intensity modulation depends on the amount of absorption, it can be used for concentration monitoring.

The third signal (10 kHz) was used for quenching spectral noise occurring in optical systems due to unexpected interference of the light beams. Multipass experiments are often affected by this interference because inside the cell the beams are spread due to diffraction and scattering on mirror surface imperfections, or just in the medium filling the cell. Scattered radiation overlaps different light spots on the mirrors, leading to periodic fringes in the cell transmittance spectrum. This is an objectionable effect because the evaluation of the absorber concentration is based on measurement of changes of transmittance by absorption in the gas sample. Any additional distortion of the spectrum can significantly spoil the detection sensitivity. We reduced these disturbances by additional laser wavelength modulation combined with averaging of this signal in the detection line [30]. The method assumes that the averaging of a periodic function over its period provides the mean value that is independent of the phase. In our experiment, the amplitude of 10 kHz sine signal (*i.e.*, the range of the wavelength modulation) was adjusted manually to the fringe period through looking at the oscilloscope for the best minimization of the interference. Signal averaging was done by the lock in the amplifier.

3. Signal analysis

The approach consisting in periodic scanning of the laser wavelength across the absorption line of the compound of interest leading to intensity modulation of the beam passing through the absorption cell is called *wavelength modulation spectroscopy* (WMS). The observation is usually done at the second harmonic of the modulation frequency. This method of absorption measurement is widely used for trace matter detection due to its immunity to noise [31]. However, a nonlinearity of the current–power characteristic of our laser (Fig. 3) forced a modification of this approach.

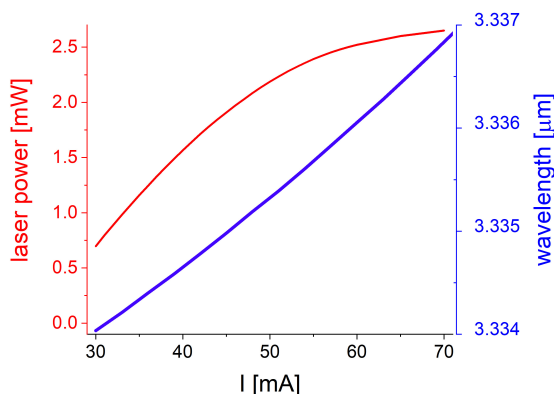


Fig. 3. Laser power and wavelength versus the supply current.

As mentioned above, we use the sinusoidal modulation of the laser current with the frequency $f = 91$ Hz. It can be described as:

$$I(t) = I_0 + \Delta I \cos \omega t, \quad (1)$$

where $\omega = 2\pi f$, I_0 denotes constant component, while ΔI is the modulation amplitude. The range of the wavelength modulation across a line of a single component covers a small part of the laser tuning range (Fig. 3). Temporal changes of the wavelength can be approximated by the following equation (2):

$$\lambda(t) \approx \lambda_0 + \frac{d\lambda}{dI} \Delta I \cos \omega t. \quad (2)$$

Both $\lambda_0 = \lambda(I_0)$ and $\frac{d\lambda}{dI}$ parameters follow from the current-wavelength characteristic shown in Fig. 3.

A nonlinearity of the current-power dependence (also shown in Fig. 3) is stronger. However, it can be well approximated with the second order polynomial (red curve). The value of R-square coefficient of about 0.9999 was achieved. Therefore, for small modulation amplitudes ΔI , we describe the temporal changes of the laser power by:

$$P(t) \approx P_0 + \Delta_P \cos \omega t + \Delta_{2P} \cos^2 \omega t. \quad (3)$$

Here, P_0 denotes a constant component, while the amplitudes of second and third harmonics are $\Delta_P = \frac{dP}{dI} \Delta I$ and $\Delta_{2P} = \frac{d^2P}{dI^2} \Delta I^2$, respectively. According to Lambert-Beer law the beam power transmitted through the absorbing sample can be expressed by:

$$P_T(t) = P(t) \exp[-\alpha(t)] \approx P(t) [1 - \alpha(t)], \quad (4)$$

where $\alpha(t)$ denotes the absorption coefficient ($\alpha(t) \ll 1$).

For small modulation depth across a narrow absorption line one can assume that the absorption coefficient also varies squarely in time:

$$\alpha(t) \approx \alpha_0 + \alpha_1 \cos \omega t + \alpha_2 \cos^2 \omega t, \quad (5)$$

where $\alpha_0 = \alpha(\lambda_0)$ is the constant component, while $\alpha_1 = \frac{d\alpha}{d\lambda} \frac{d\lambda}{dI} \Delta I$ and $\alpha_2 = \frac{d^2\alpha}{d\lambda^2} \left(\frac{d\lambda}{dI}\right)^2 \Delta I^2$.

Combining the equations (3)–(5) results in:

$$P_T(t) = \left(P_0 + \Delta_P \cos \omega t + \Delta_{2P} \cos^2 \omega t\right) \left(1 - \alpha_0 - \alpha_1 \cos \omega t - \alpha_2 \cos^2 \omega t\right). \quad (6)$$

We assume that the photodetector signal is proportional to the transmitted power: $s = \gamma P_T$, where γ denotes the photodetector efficiency. Using the trigonometric identities, the signal can be expressed in the following form:

$$\begin{aligned} s(t) = \gamma P_T(t) = \gamma & \left(P_0 - P_0 \alpha_0 + \frac{\Delta_{2P} - P_0 \alpha_2 - \alpha_1 \Delta_P - \alpha_0 \Delta_{2P}}{2} - \frac{3}{8} \alpha_2 \Delta_{2P} \right) \\ & + \gamma \left(\Delta_P - P_0 \alpha_1 - \alpha_0 \Delta_P - \frac{3\alpha_2 \Delta_P + 3\alpha_1 \Delta_{2P}}{4} \right) \cos \omega t \\ & + \frac{\gamma}{2} (\Delta_{2P} - P_0 \alpha_2 - \alpha_1 \Delta_P - \alpha_0 \Delta_{2P} - \alpha_2 \Delta_{2P}) \cos 2\omega t \\ & - \frac{\gamma}{4} (\alpha_2 \Delta_P + \alpha_1 \Delta_{2P}) \cos 3\omega t \\ & - \frac{\gamma}{8} \alpha_2 \Delta_{2P} \cos 4\omega t. \end{aligned} \quad (7)$$

When the laser wavelength and power linearly depend on the supply current ($\Delta_{2P} = 0$, $\alpha_2 = 0$), the amplitude of second harmonics of the signal (7) is reduced to the form of $\gamma\alpha_1\Delta_P/2$, *i.e.*, it is proportional to the absorber concentration and the higher harmonics do not occur. Therefore, the usual measurements with WMS are performed at the second harmonic [32]. In the case of square character of current-power relation (3), the value of the constant component of the signal (7), as well as the amplitudes of the first, second and third harmonics, are complicated combinations of various parameters. That spoils the linearity between the amplitudes and the absorption coefficient (α_0) or its derivatives (α_1 or α_2) at these frequencies. Due to that, the amplitude of the second harmonic depends not only on the absorber concentration, but also on the Δ_{2P} parameter which is not related to absorber density. However, the amplitude of fourth harmonic is directly proportional to the second derivative of the line shape function (α_2), *i.e.*, it is proportional to absorber concentration. Therefore, in our experiment the detection of the selected compounds in the sample was performed at 4ω .

4. Results

In order to test linearity of our ethane sensor we used a method of stepwise dilution of calibrated reference mixture (Messer, 1 ± 0.05 ppm of C_2H_6 in nitrogen). In the first step, this mixture was introduced into the multipass cell at the pressure of 101.3 hPa. After signal collecting the mixture was diluted with nitrogen evaporated from its liquid phase. The pressure was then raised to 202.6 hPa. After a time period of about 15 minutes, necessary to achieve a good mixing of the gases, the pressure was reduced again to 101.3 hPa. That produced the mixture with half the density of ethane in respect to the previous state. Then the signal was collected again. Consecutive operations of diluting and signal registration were repeated. The determination of C_2H_6 concentration was based on a comparison of amplitudes for certain concentrations with the amplitude of the signal provided by the reference mixture. The uncertainty of the ethane concentration achieved in the gas sample after k steps of the reference mixture dilution can be evaluated from the following formula:

$$\frac{\Delta n_k}{n_k} = \sqrt{\left(\frac{\Delta n_r}{n_r}\right)^2 + (k+1)\left(\frac{\Delta p}{p}\right)^2}, \quad (8)$$

where $\Delta n_r/n_r = 5\%$ denotes the uncertainty of the reference mixture concentration, while $\Delta p/p = 1\%$ is the uncertainty of gas pressure measurement with a MKS Baratron (model 722B). The value of $\Delta n_k/n_k$ changes from the initial 5% to about 6.2% at step 12 of the dilution.

The data collected in this way are shown in Fig. 4. Laser modulation was performed at the absorption line center and the lock-in time constant of 1 s. The sensor worked linearly down to the concentration of 1 ppb (about $2.7 \cdot 10^9 \text{ cm}^{-3}$). For this concentration the Allan deviation plot was performed as well [33]. The lock-in signal output was connected to the digital oscilloscope which was recording 1000 samples per second. Then, samples were averaged and standard deviation was calculated. These parameters were changing in the function of averaging time, reaching a minimum near 20 s (Fig. 5). The precision of approximately 80 ppt was achieved for this optimal integration time. It means that the practically achieved detection threshold of 1 ppb is sufficient for the study of air exhaled from human lungs since the morbid level of ethane is about 3.5 ppb [34].

The H_2O measurement by such optical sensor may also be useful. The water content in ambient air was assumed as a reference concentration. The temperature of 23°C and the relative

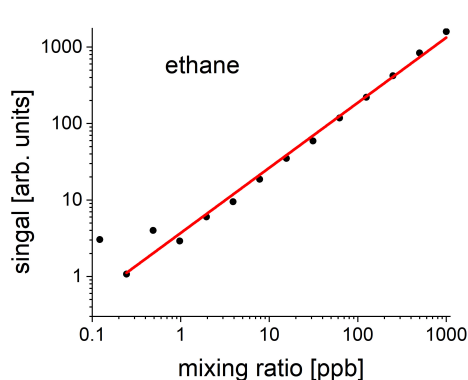


Fig. 4. Results of measurement of ethane concentration.

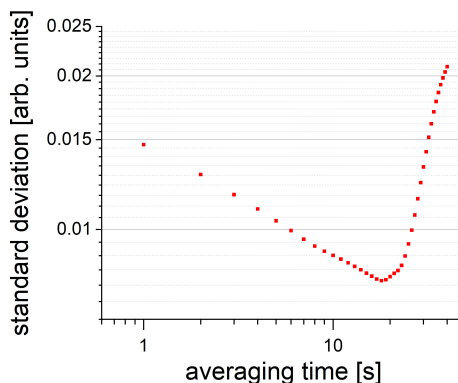


Fig. 5. Allan deviation plot for ethane measurement.

humidity of 35% were registered in the laboratory during our experiment. That corresponded to $2.4 \cdot 10^{17} \text{ cm}^{-3}$ of H_2O molecules according to the Magnus formula [35]. The sensing was done at $3.3342687 \text{ }\mu\text{m}$ line (Fig. 1b). The procedure of consecutive dilution was also applied in this case. The results of the measurements are shown in Fig. 6a. The sensor worked linearly up to the H_2O dilution level of about 0.1 ($2.4 \cdot 10^{16} \text{ cm}^{-3}$).

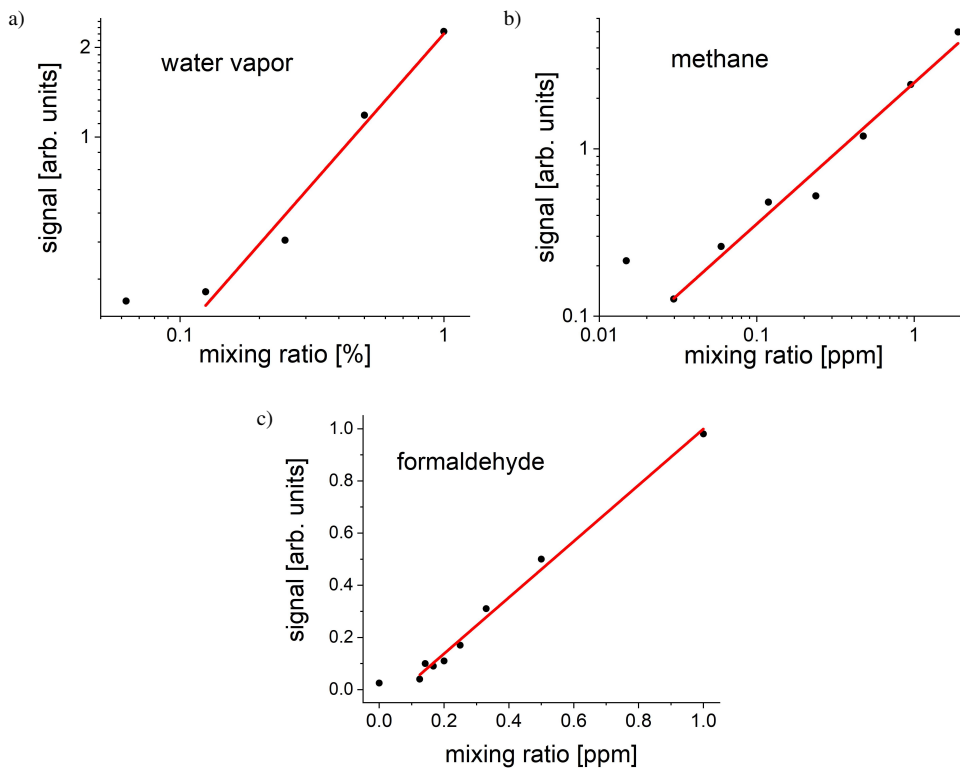


Fig. 6. Results of measurement for water vapor (a), methane (b) and formaldehyde (c).

Water vapor measurement with such optical sensor is important since it can be used for its calibration when ethane reference mixture is not available. Moreover, absolute determination of H₂O concentration in breath can be used for evaluation of water content in the body, which is important in the case of monitoring of heart failure treatment. Additionally, it can potentially be used in all conditions that require hydration monitoring (including the treatment of the elderly and unconscious) and hydration monitoring for the treatment of severe kidney failure – including dialysis.

A relatively high absorption coefficient of methane (Fig. 2b) allows also for the detection of this constituent. It was identified as a biomarker of colonic fermentation and intestinal problems [36]. Its morbid level was determined to be 10 ppm (20 ppb for smokers).

We tested our sensor for the methane detection at 3.3343746 μm line since it is relatively weakly interfered with by H₂O absorption. Because a calibrated mixture was not available, the mean CH₄ concentration in ambient air (1.9 ppm) was accepted as an approximate reference concentration [37]. The results are shown in Fig. 6b. The sensor worked linearly up to the dilution level of 1/64. It means that the usable detection level of methane in our system is about 30 ppb. Sensitive optical detection of methane was already performed in various NIR and MIR spectral ranges using single-pass spectrophotometry, WMS and photoacoustic approaches [38, 39]. Comparable detection limits were achieved.

Our sensor was also used for formaldehyde detection. Formaldehyde is a toxic, mutagenic and possibly carcinogenic gas that has also been identified as a potential lung and breast cancer biomarker [40–45]. The morbid level of the formaldehyde concentration is not well established. Early findings claimed that H₂CO concentration of 0.45–1.2 ppm was observed in exhaled breath from breast cancer patients, compared to normal levels of 0.3–0.6 ppm [46, 47]. Our detection of this constituent was done at 3.3349674 μm. Consecutive stepwise dilution of calibrated reference mixture (Messer, 1 ± 0.05 ppm of H₂CO in nitrogen) was also used and the results are shown in Fig. 6c. The sensor worked linearly up to the threshold value of 0.1 ppm. The formaldehyde absorption line mentioned above is rather weak and affected by methane interference (Fig. 1b). Therefore, the sensitivity is rather poor comparing to other optical approaches like those in the 3.6 μm range where single ppb or even sub-ppb detection limits were achieved [48, 49]. Nevertheless, our result is sufficient for evaluation of the formaldehyde content in human breath.

It is also necessary to check the long-term stability. Measurements of the reference mixture from the cylinder made three days apart did not differ by more than 4%. In addition, for the entire duration of the experiments (about a month) there was no need to change the parameters of the generator (both the variable component and the constant component), which means that the system is stable over time.

5. Conclusions

In this study we have demonstrated an optical sensor designed for absolute measurement of ethane concentration in air exhaled from human lungs. Careful analysis of the spectrum of this compound in the 3.33 μm range provided an opportunity to select the absorption line (3.3368035 μm) and the appropriate pressure (101.3 hPa) enabling to measure C₂H₆ directly in human breath, despite naturally occurring (in significant amounts) interferents such as water and methane. The achieved sensitivity of the sensor is sufficient for clinical trials with proper linearity across three orders of magnitude (from 1 ppm to 1 ppb). In addition, this system, unlike many others, offers the opportunity to measure methane, water vapor and formaldehyde with a good linearity and sensitivity that enables to study the correlations between these compounds in breath.

The system uses an innovative approach to signal analysis of the fourth harmonic (WMS-4f) which is suitable for semiconductor lasers with nonlinear current–power characteristics. Moreover, the use of the optical noise suppression method additionally increases its immunity to interference caused by the superimposition of laser spots in optical systems, which is a common obstacle when using multipass cells, especially with long optical path and low volume.

Mateusz Winkowski conducted the experiment, while Tadeusz Stacewicz supervised it. Both authors prepared the paper.

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