Performance analysis of diode optopair gas sensors

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ABSTRACT

Analytical description of the transfer function of an optical gas sensor takes into account a fine structure of gas absorption spectra and spectral characteristics of optopair elements and their temperature drift. Such approach permits one to estimate as early as at the designing stage the expected accuracy of measurements that can be provided by non-dispersive infrared (NDIR) gas sensors of different configuration as the environment temperature changes and/or in the presence of interference from foreign gases. Moreover, analytical description of the transfer function allows increasing the accuracy of gas concentration measurements. Calculated and experimental results of the study of laboratory models of small-size NDIR sensors based on mid-infrared (3-5 μm) immersion diode optopairs are given. The presented results confirm the validity of the proposed approach for the NDIR gas sensor description and promising prospects for using the sensors based on immersion diode optopairs in portable gas analysers.
Keywords: NDIR gas sensor, immersion lens diode optopair, sensor instrument function, gas sensor transfer function.

1. INTRODUCTION

In general, optical nondispersive methods for detection and measurement of gas concentration in the 3-5 μm spectral range (mid-IR) are implemented in gas sensors that belong to portable meters. In this placement class, potentialities of gas analysis optical methods are superior to those of electrical chemical and catalytical techniques because they provide higher speed of operation, greater selectivity, corrosive medium stability and longer period of service.

Conventionally, sensors based on radiation heat sources and broadband radiation detectors together with narrowband (interference) filters are used in IR analysers. Recently, they have been substituted by optical sensors based on semiconductor light emitting- and photodiodes [1-2] that allow introducing essential improvement into the sensor design, i.e., not using mechanical modulators, interference filters, to reduce power consumption and basic size, and to improve metrological potentialities on the whole. At the same time, the use of semiconductor materials (whose essential property is the shift of spectral characteristics with increasing temperature to the long-wavelength spectrum region) leads to origination of temperature drift of sensor readings, so that it becomes necessary to develop special techniques for their compensation.

The spectral characteristic of semiconductor mid-IR light emitting- and photodiodes is relatively narrow ($\Delta\lambda/\lambda \approx 0.1$), which makes it possible not using interference filters in NDIR gas sensors. However, in a number of cases, foreign gases whose absorption spectra overlap the NDIR gas sensor sensitivity band may be present in a gas cell and may introduce an error into the measurement of concentration of a gas under analysis (e.g., the effect of CO_2 on CO concentration measurement, effect of nitrous monoxide N_2O on CO_2 concentration measurement, hydrocarbon segregation, etc.) Therefore it is essential to develop a device that would allow one as early as at the stage of sensor designing to evaluate errors introduced by extraneous gases and to outline ways for their reduction.

When carrying out measurements within a wide range of gas concentrations and changeable environmental conditions, in case radiation sources in NDIR gas sensors are not monochromatic, one uses, as a rule, experimental calibration dependencies of a sensor output signal on test concentration of a gas under analysis. It is clear that it is necessary to proceed from tabular calculation procedures of gas concentration to analytical ones in order to increase the accuracy of measurements. Earlier [3, 4] we have proposed a model of optical gas sensor in which the NDIR gas sensor is described

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from the point of view of measurement techniques. It is based on the analytical calculation of instrument and transfer functions of an optical gas sensor and permits one to solve the above mentioned problems of nondispersive gas analysis. Apart from this, the approach allows:

- to calculate performance limits for sensor sensitivity, i.e., limit of detection (LOD), absolute and relative measurement errors in a wide range of changes of gas under analysis concentrations;
- to compare characteristics of sensors with different hardware components;
- to optimize optical and electronic sensor circuits for various practical problems;
- to determine the value of the signal-to-noise ratio of a signal under detection (which is defined by parameters of electronic circuits of signal formation and processing), necessary for obtaining a required measurement accuracy.

The aim of the present study is to show the capabilities of the suggested approach for calculation of the main parameters of sensors based on new sources and detectors of IR radiation: immersion diode optopairs, that have been developed at Ioffe Physical-Technical Institute of the Russian Academy of Sciences [5-7]. Gases with the absorption line lying in the mid-IR range (3-5) μm: carbon dioxide (CO_2, 4.26 μm), hydrocarbons (by the example of ethylene C_2H_4, 3.3 μm), and carbon monoxide (CO, 4.66 μm) were taken as examples.

2. ANALYTICAL MODEL OF AN OPTICAL GAS SENSOR

The operation of optical gas sensors that are spectral measurement devices is based on the well-known absorption law[4] connecting the intensity of monochromatic radiation (λ) transmitted through a gas with spectral absorption coefficient α(λ) at an interaction length L with its concentration C:

$$I(C,\lambda) = I_0(\lambda)\cdot\exp[-\alpha(\lambda)\cdot L\cdot C] \qquad (1)$$

From the point of view of measurement techniques, the main element of a non-dispersive optical gas analyser is a measuring transducer, i.e., an optical gas sensor performing the transformation of an input quantity C into a quantity to be measured I(*C*,λ). The principal point that must ensure the analytical model of such sensor is to determine the functional dependence (transformation equation) of its output quantity on the input one, gas concentration C. The analysis of thus obtained sensor transfer function together with the value of the signal-to-noise ratio determined by parameters of electron circuits for signal formation and processing permits one to determine such parameters as threshold sensitivity, absolute and relative measurement errors in a wide range of concentrations of a gas under study that are important for estimating the quality of measurement devices.

The sensor consists of a radiation source $I_0(\lambda)$ that is conjugated in a number of cases with a spectral filter F (λ), gas cell and detector of radiation. The gas under analysis modulates the intensity of source radiation during its passing through the gas cell. An electric signal U (I_0, C, λ) that depends on the intensity of probing radiation I_0 (λ) and contains information on gas concentration C is formed at the sensor output. It is clear that the parameter $I_0(\lambda)$ should be excluded in order to unambiguously determine the value C by a measured signal U (I_0,L, C,λ). This condition may be fulfilled either by keeping the value $I_0(\lambda)$ at a certain (constant) level that is determined before the beginning of measurements or by introducing an additional 'reference' channel in which a quantity proportional to I_0 (λ) is measured. There are different technical methods for excluding the influence of $I_0(\lambda)$ on measurement results; however, their analysis is out of the scope of the present study. Therefore we shall consider the transmittance factor of a cell with gas as an output signal of the optical sensor. The transformation equation that describes the sensor transfer function for probing radiation in a frequency band $\Delta\lambda = \lambda_2 - \lambda_1$ takes into account spectral characteristics of sensor elements and undesired absorption caused by foreign gases. Finally, it permits one to calculate the required gas concentration C at the gas sensor input by measuring the value τ (*C*, *L,* λ) at its output. The equation is described by the following integral expression:

$$\tau(C,L,T)=\frac{U(C,L,T)}{U_0(T)}=\frac{\int_{\lambda 1}^{\lambda 2} R_{PhD}(\lambda,T)\cdot P_{LED}(\lambda,T)\cdot F(\lambda)\cdot\exp[-\alpha(\lambda)\cdot L\cdot C]\cdot\prod_{1}^{N}\exp(-\alpha_i(\lambda)\cdot L\cdot C_i)d\lambda}{\int_{\lambda 1}^{\lambda 2} R_{PhD}(\lambda,T)\cdot P_{LED}\ (\lambda,T)\cdot F(\lambda)d\lambda} \quad (2)$$

where $R_{PhD}(\lambda,T)$ is the spectral sensitivity of a photodetector,
$P_{LED}(\lambda,T)$ is the spectral power of a source of radiation,
$F(\lambda)$ is the spectral characteristic of a filter,
$\alpha(\lambda)$ is the spectral absorption coefficient of a gas under study,
$\alpha_i(\lambda)$ are spectral characteristics of absorption coefficients of foreign gases with concentration C_i,
L is the length of interaction of the probing radiation with the gas.

The temperature parameter T in the function of spectral characteristics of the source ($P_{LED}(\lambda, T)$) and detector ($R_{PhD}(\lambda, T)$) is introduced into (2) in order to take the effect of sensor temperature on the values of gas concentration being measured into account.

Determination of the measurement error value with the change of environment temperature and/or determination of the range of operation temperatures within which this error does not exceed a given value is one of the most important problems when working out the measurement techniques. The numerical value of this error together with characteristics of sensitivity and accuracy of measurements can be obtained by numerical differentiation of (2) for the sensor transfer function. Thus, the transfer function of an optical gas sensor $\tau(C)$ is the principal functional dependence, in accordance with which various types of sensors can be compared with respect to sensitivity and the obtained accuracy can be calculated when using them in gas sensors. In order to solve these problems it is necessary to know analytical expressions for spectral characteristics of the absorption coefficients of a gas under study and foreign gases, those of sensor optical elements and their temperature dependencies.

2.1. Spectral distribution of gas absorption coefficient

Radiating (absorbing) ability of gas molecules in the IR spectrum range is caused by vibrational rotational mechanism of oscillations of molecules and it has a clearly expressed line-structure. In this case, gas absorption bands consist of a great number of spectral lines that are spaced practically uniformly apart, their width being determined by the probability of collisions between gas molecules. Under standard measurement conditions (STP), the half-width of these lines (FWHW) is equal to about 0.1 cm^{-1} and the spectral line shape is described by the Lorentzian that determines the radiation (absorption) coefficient for each spectral component [9].

In order to find the absorption value of probing radiation during its passing through a gas, the spectral absorption coefficients ($\alpha(\nu)$, cm^{-1}) are used. We have applied the analytical model of spectral distribution of gas absorption coefficients calculated from the tables of line intensity of gas radiation $S(\nu_0)$ that meets the following requirements:

- spectrum of gas absorption coefficient is described by the sum of Lorentz distributions with different resonance frequencies ν_0 and amplitudes $S(\nu_0)$ and equal values of a line half-width σ_L:

$$\alpha(\nu)=\sum_i \frac{S(\nu_i)}{\pi}\cdot\frac{\sigma_L}{\sigma_L^{\,2}+(\nu-\nu_i)^2} \quad (3)$$

- spectra of absorption coefficients of all gases are given within the spectral band 2000 – 3350 cm^{-1} (radiation wavelengths are equal to 3-5 μm) with spacing 0.01 cm^{-1}. The fulfillment of this condition makes it possible to simulate absorption spectra of gas mixtures and to take the effect of foreign gases on the sensor transfer function into account.
- the model takes into account only the lines with the intensity $S \geq 0.1$ cm · atm under standard measurement conditions.

When developing mathematical models, one of the principal points is the choice of check criterion for their validity. Experimental gas absorption spectra from the PNNL database (Pacific Northwest National Laboratory)[10] have been taken as reference spectra for checking the validity of a model being developed. The spectra were taken with a Fourier spectrometer with the resolution equal to 0.1 cm^{-1} within the range 6500-600 cm^{-1} and gas concentration equal to C = 1 ppm at the absorption wavelength L = 1 m.

We used the tables of the international database HITRAN [11] (high resolution transmission molecular absorption database) for setting parameters ν_0 and S, whereas the value σ_L was evaluated from the coincidence of the gas absorption spectra calculated in accordance with our model and experimental spectra from the data of the PNNL laboratory.

Good matching of the absorption spectra calculated by using the proposed model and PNNL experimental spectra has been obtained at σ_L =0.085 cm^{-1}/atm for carbon dioxide (CO_2), at σ_L =0.075 cm^{-1} /atm for carbon monoxide (CO), and at σ_L =0.11 cm^{-1} /atm for ethylene (C_2H_4).

2.2 Sensor instrument function

The main element of a NDIR gas sensor is an optopair, a source and a detector of radiation that are matched optically and spectrally; sometimes (usually when heat sources are used) an additional narrow-band spectral filter is applied. The optopair spectral characteristic is described by the product of spectral characteristics of a filter and radiation source and detector; it determines the sensitivity of a sensor to a gas and is called the 'instrument function' of a sensor.

Immersion 'flip-chip' diodes [4] were chosen in this study as hardware components for NDIR gas sensors. At present, in our opinion with regard to the set of technical specifications they meet most completely the requirements imposed upon the sensors of wide-scale use. The analysis of spectral characteristics of light-emitting diodes LED34SC-, LED42SC- and LED47SC- type and photodiodes of a PD34SC-, PD42SC- and PD47SC- type [7] taken within a temperature range between -20 and +60°C and averaged with respect to a set of samples demonstrated that they are well approximated by Lorentz distribution functions $L(\lambda_{max}, \Delta\lambda)$ for LED and by a sum of Gauss distributions $G(\lambda_{max}, \Delta\lambda)$ for photodiodes:

$$P_{LED}(\lambda,T) = L(\lambda_{\max}(T),\Delta\lambda(T)) = \frac{P_0}{\pi}\cdot\frac{\Delta\lambda(T)}{\Delta\lambda(T)^2+(\lambda-\lambda(T)_{\max})^2}$$
$$R_{PhD}(\lambda,T) = R_0\cdot\left[k_1\cdot G1(\lambda_{\max}(T),\Delta\lambda(T)) + k_2\cdot G2(\lambda_{\max}(T)-0.35,0.2)\right] \quad (4)$$

The PD spectral functions are slightly wider than those for LED. First of all, this difference is due to the fact that high-energy radiation (beyond the edge of fundamental absorption) is absorbed efficiently in a photodiode and contributes into the value of photocurrent under certain conditions. By contrast to this, in LED, the probability of emission of a photon with high energy that exceeds the energy of a band gap width decreases exponentially with a quanta energy increase and the LED spectrum is always relatively narrow.

The position of the maximum of spectral functions (value λ_{max}) obeys the linear law with a shift temperature coefficient 3-5 nm/degree that is the same for LED and PD of one and the same spectral range. As an example, Fig.1 presents the dependence of the position of the radiation wavelength spectral line maximum upon temperature for a sample LED42SC**.** As can be seen from the Figure, the shift of the maximum of the LED emission line is well approximated by a linear dependence of the following form:

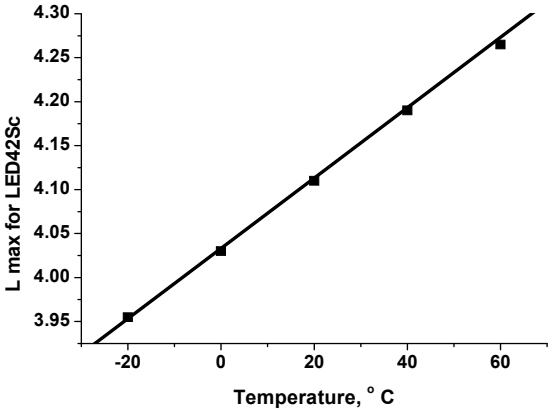


Fig.1. Dependence of λ_{max} for LED42SC upon temperature.

$$\lambda_{max}(\mu m) = \lambda_{max}(T_0) + 0.004*(T - T_0) \quad (5)$$

where T is LED current temperature.

In order to estimate the half-width of a radiation spectral line within the temperature range 0-50 ^{0}C one may use the relation: $\Delta\lambda(T) = k \cdot \lambda_{max}(T)$, where $k \approx$ 0.1-0.15 as an approximate expression. The temperature dependence $\Delta\lambda(T)$ becomes nonlinear with increasing temperature range.

The identity of temperature dependencies of spectral characteristics of light emitting diodes and photodiodes permits one to state that the shape of the instrument function of an optical gas sensor does not change with temperature so that different optopairs can be described by the instrument function with a unique parameter $\lambda_{max}(T)$:

$$A(\lambda,\lambda_{max}(T)) = R_{PD}(\lambda,T)\cdot P_{LED}(\lambda,T)\cdot F(\lambda) \quad (6)$$

2.3 Sensor transfer function. Sensitivity and accuracy of sensors

Taking into account the instrument function notion given in the previous section, the sensor transfer function is written as:

$$\tau(C,L,T) = \frac{\int_{\lambda 1}^{\lambda 2} A(\lambda,\lambda_{\max}(T))\cdot\exp[-\alpha(\lambda)\cdot L\cdot C]\cdot\prod_{1}^{N}\exp(-\alpha_i(\lambda)\cdot L\cdot C_i)d\lambda}{\int_{\lambda 1}^{\lambda 2} A(\lambda,\lambda_{\max}(T))d\lambda} \quad (7)$$

Fig.2 shows instrument and transfer functions of sensors based on immersion optopairs of LED34SC + PD34SC (Fig.3a), LED42SC + PD42SC (Fig.3b) and LED47SC +PD47SC (Fig.3c) types designed for analyzing hydrocarbons, carbon dioxide and carbon monoxide, respectively.

The slope of the transfer characteristic S(C) = dτ/dC determines the sensitivity of a sensor that depends on the value of an input signal C (gas concentration) due to the nonlinearity of the transfer characteristic τ(C) and it will be essentially different for different ranges of concentration measurement. In absolute terms the value of sensitivity is determined as dC = dτ/ S(C). If we take that the minimum recorded change dτ is equal to 1/Ψ for a given signal-to-noise ratio (Ψ) of the sensor measurement circuit, then the absolute error of measurements and the notion of the limit of detectability that is related to it can be calculated by using the relationship dC =1/ (Ψ· S(C)).

3. EXPERIMENTAL RESULTS

In order to demonstrate the capabilities of the model and to perform the validity check for the above-considered approach we have fabricated laboratory models and studied characteristics of optical sensors of ethylene, carbon dioxide and carbon monoxide gases based on immersion diode optopairs with instrument functions considered in Sec.2.2. The operational speed of the sensors was determined by the parameters of low-frequency filters in the photodetector signal processing circuit and was equal to 0.1 - 1 s. Current generator parameters were as follows: pulse probing radiation with 20kHz frequency in a 'meander' mode, average radiation power P_{CW} =10-100 mcW at an average LED current I = 200 mA. The PD detectability is $D^*=10^9$ -10^{11} cm $Hz^{1/2}$ W^{-1}. The immersion optics angle was equal to 20^0 or less. At small sizes of the gas cell (L≤5 cm) it provides high efficiency of using LED radiation energy in different designs of sensors. Moreover, it allows obtaining the signal-to-noise ratio Ψ at the output of sensor signal detection and processing circuits at the level equal to (1-5)·10^3 for the values of the operational speed equal up to10 readings per second.

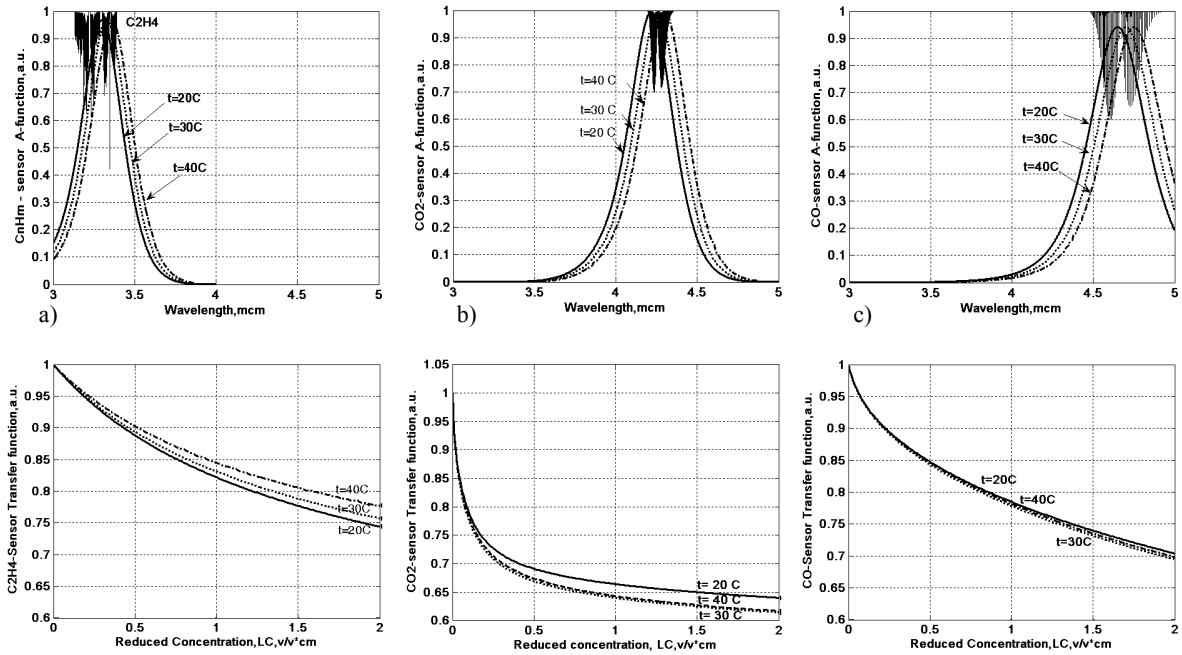


Fig.2. Instrument and transfer functions of sensors based on immersion optopairs of LED34SC + PD34SC (Fig.3a), LED42SC + PD42SC (Fig.3b) and LED47SC +PD47SC (Fig.3c) types designed for analyzing hydrocarbons, carbon dioxide and carbon monoxide, respectively.

3.1 Two channel gas (CO_2 +C_2H_4) sensor laboratory model

The model was fabricated with using optopairs of the LED42Sc (the measured value λ_{max} (20^0C)=4.11 μm) + PD42Sc (the measured value λ_{max} (20^0C)=4.08 μm) type, which gives the resulting instrument function with the calculated value λ_{max}(20^0C)=4.10 μm and optopairs LED34Sc (the measured value λ_{max} (20^0C)=3.3 μm)+PD34Sc (the measured value λ_{max} (20^0C)=3.3 μm). The sensor optics consists of a spherical mirror that permits matching the LED radiation with PD [12]. The sensor model provides the possibility to change the length of the gas cell, to digitize and to transmit current values of an optopair signal and temperature by RS 232 interface for subsequent computer processing. The operational speed of the sensor was equal to 100 ms (10 readings per second). Additional interference filters (F(λ)=1)have not been used in this model.

The model has been tested at D.I.Mendeleyev Research Institute for Metrology (St.Petersburg) with using standardized mixtures CO_2 in N_2 for carbon dioxide and ethylene concentrations ranging from 0.01 up to 50 vol. % and from 0.05 up to 50 vol.%, respectively. The system has been blown with pure nitrogen after every measurement. Fig.3 shows the shape of the sensor output signal for L =4 cm. The temperature of sensors during the experiment changed smoothly from 30 to 40^0C. As can be seen from the signals presented in Fig.3, mutual influence (crosstalk) of channels is absent and there is high operational speed and high value of the sensor signal-to-noise ratio (SNR). In our estimations, the SNR value was equal to ca. $3\cdot10^3$ for each channel in case the operational speed up to 10 readings per second.

Fig.4b presents experimental values of the sensor C_2H_4 transfer function in case the length of the gas cell of the gas sensor laboratory model is equal to 4.5 cm (●) and Fig.4a shows those of a CO_2 sensor (the gas cell length is equal to 0.25 cm (▾) and 4 cm (■)) when the mixture of gases CO_2 + N_2 of different concentration passes through it. As can be seen from Fig.4, there is a good matching of estimated and experimental data. The discrepancy does not exceed 0.5% and 2% for CO_2 and C_2H_4, respectively, which may be related to uncontrolled changing of the sensor temperature in the given experiment. Despite these deviations, the obtained results indicate the usefulness of the suggested concept and its validity for constructing gas sensors with given parameters.

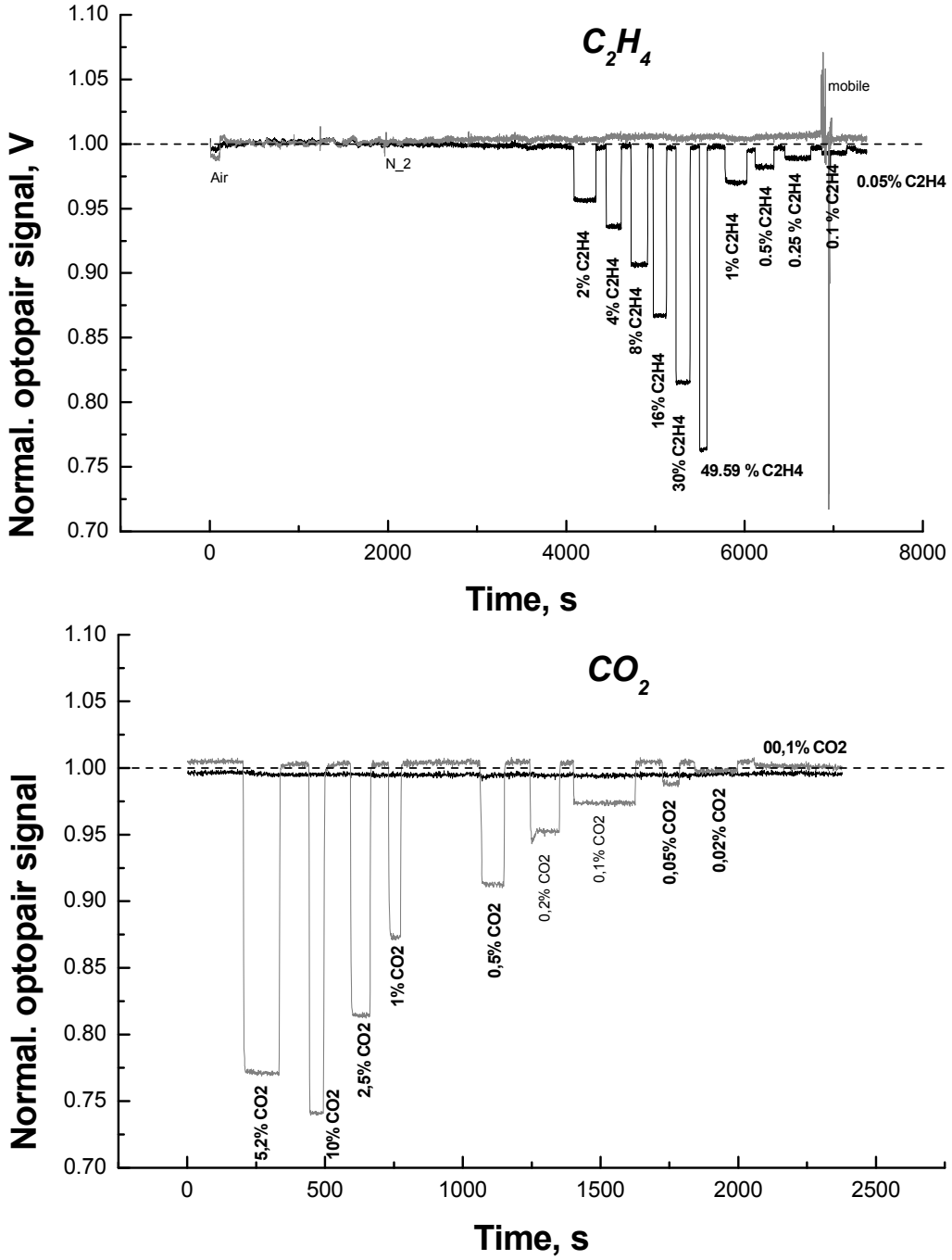


Fig.3. The shape of the sensor output signal for L =4 cm: the gray and black lines are for CO_2 and C_2H_4 channels, respectively.

Let us estimate the measurement accuracy of the CO_2 concentration that can be achieved when using the given experimental model with the gas cell length equal to 4 cm and experimentally obtained value of the signal-to-noise ratio

equal to Ψ=3000 for the operational speed equal to 10 readings per second. Fig.5 demonstrates the results obtained by differentiating the transfer function of the CO_2 sensor with the instrument function that has λ_{max} (20^0C)=4.22 μm. The estimated values of the detection limit (LOD) at the 100 ppm level and the relative measurement error at the level equal to 1-3% within a wide range 0.3-10% of CO_2 concentrations at the operational speed equal to 10 readings per second refers to the best specimens of carbon dioxide portable sensors.

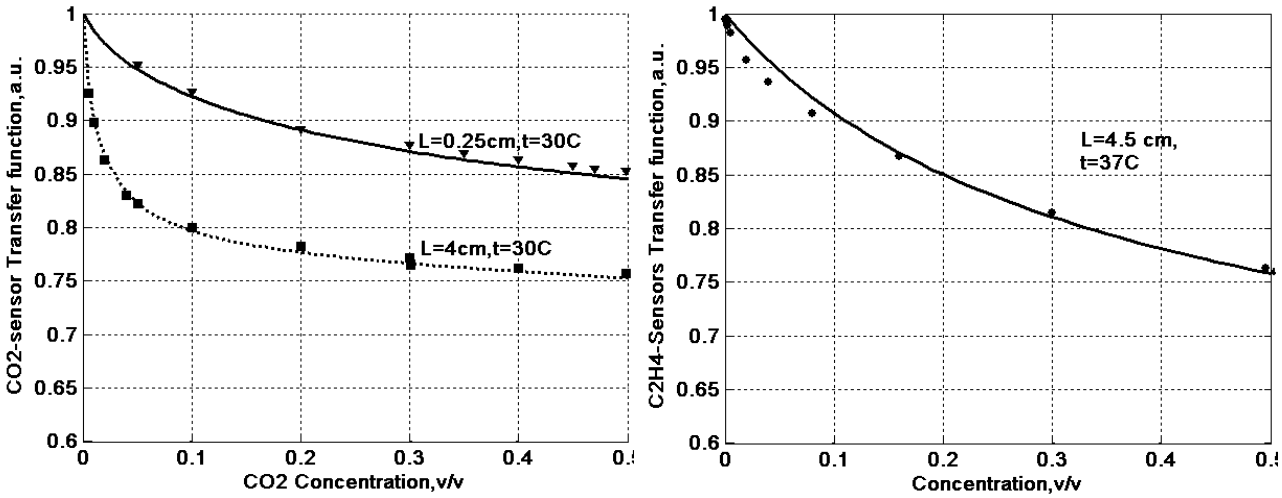


Fig.4. Experimental values of the sensor CO_2 transfer function (a) for the length of the gas cell equal to 0.25 cm (▼) and 4 cm (■)and those for a C_2H_4sensor (b) with the gas cell length equal to 4.5 cm (●).

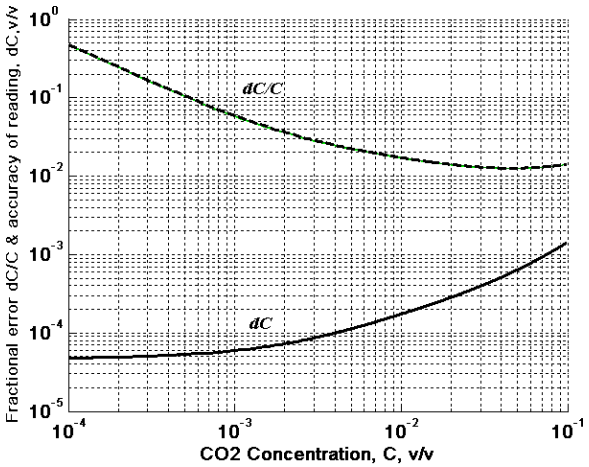


Fig.5 . Accuracy of the CO_2 sensor readings d(CL), v/v*cm and relative sensitivity dC/C, % for immersion lens diode sensor A-function with λ_{max}(20^0C)=4.22 μm.

3.2 Carbon monoxide sensor

One of the main problems in the measurement of monoxide small concentrations is the presence of carbon dioxide in atmosphere whose absorption line lies in the operating region of the CO-sensor instrument function (Fig.6). It can lead to considerable procedure errors when calculating the CO concentration by the measured value of an absorption signal. The foreign gas (in this case, CO_2) effect may be decreased by suppressing the spectral components in the sensor instrument function corresponding to it. One of possible ways of the suppressing is to introduce a 'gas lock filter', an element filled with a foreign gas of high concentration, into a sensor. It is convenient to describe the gas lock filter with a reduced concentration parameter $C_F L_F$, where L_F is the gas filter length and C_F is the concentration of gas in the filter with taking into account the pressure. The introduction of such additional element in the analytic description of the instrument function of a sensor, is equivalent to setting the characteristic of the spectral filter of the following type:

$$F(\lambda) = \exp(-\alpha_{CO2}(\lambda) \cdot CL_F) \tag{8}$$

The sensor model was made using optopairs of LED47Sc (the measured value λ_{max} (20^0C) = 4.65 μm) + PD47Sc (the measured value λ_{max} (20^0C) = 4.65 μm) type. The sensor model (Fig.7) is performed according to a two-pass optical scheme with using a spherical mirror[12]. The gas cell is divided into two sections, which permits introducing the gas lock filter. The frequency of the radiation modulation was equal to 20 kHz in the meander mode at the LED average current equal to 200 mA.

Fig.6 shows the shape of the instrument function of the CO sensor when introducing a 'CO_2 gas filter-trap' with $C_F L_F$ =1 (L_F =1 cm at the 100% CO_2 concentration) into the gas cell.

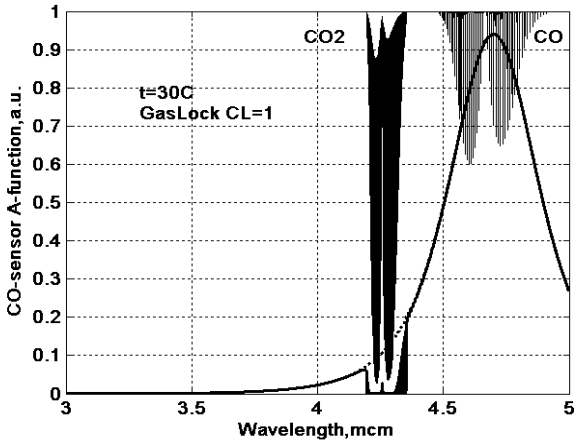


Fig.6. CO-sensor instrument function with a CO_2 gas filter (solid line) and without gas lock filter (dotted line).

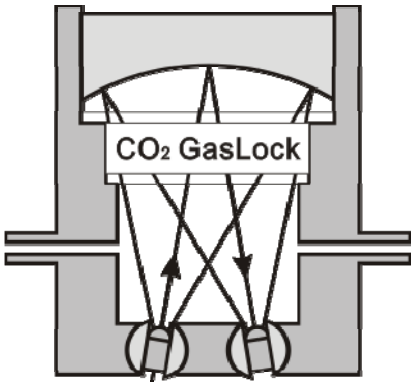
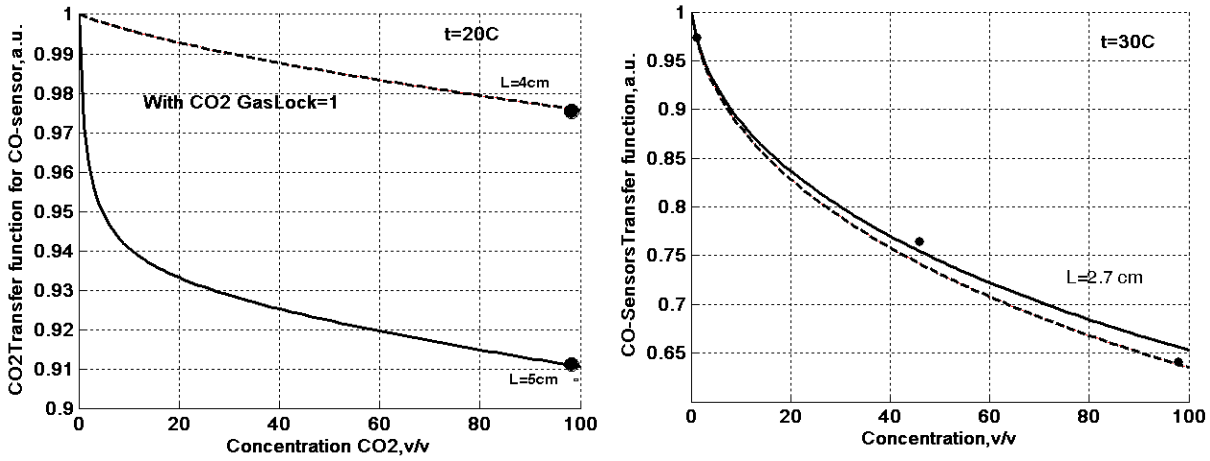


Fig.7. CO-sensor model with a CO2 gas lock filter.

Fig.8a presents the estimated dependencies of the CO-sensor output signal when applying CO_2 to its input with (dotted line) and without (solid line) gas filter in it. In the Figure, the points designate experimentally obtained absorption values for 100% CO_2 in the model of the sensor under study. It can be seen in the Figure that the sensitivity of the CO-sensor to carbon dioxide decreases considerably in the case where a gas filter is present, particularly within the range of small concentrations. Fig.8b shows the calculated transfer characteristics of a CO-sensor output signal without a filter and with CO_2 gas filter (parameter $C_F L_F$ =1) and experimental values of transmittance of the sensor with a gas filter obtained for the case when carbon monoxide of different concentrations (the gas cell operating length L is equal to 2.7 cm) is applied to its input. In this study, temperature of the model was equal to 30 ^{0}C. It can be seen in the Figure that the presence of the gas lock filter in the gas sensor leads to the increase of its sensitivity to carbon monoxide at the expense of decrease of noninformative spectral components in its instrument function.

The measured value of the signal-to-noise ratio (Ψ) at the output of the sensor in a single pulse was equal to 15, which gives the value Ψ≈ 2 000 when averaging 20,000 pulses per 1 second. For this Ψ value, the values of the CO sensor sensitivity obtained by differentiating its transfer function (Fig.8b) are equal to about 200 ppm.

The requirements to the sensitivity of carbon monoxide sensors can be formulated by taking into account its effect on a human state that is shown as CO toxicity curves . The required values of the sensitivity and operational speed of the CO-sensor should be at the level 100 ppm and operation speed equal to 1-10 s. Fig.9 presents results of the estimation of the sensitivity of the CO-sensor experimental model for two different lengths of the gas cell and operational speed equal to 10 s. The calculated values of the sensitivity at the level 20-50 ppm match entirely the above-stated requirements.



a) b)

Fig.8. Transfer functions of the CO-sensor output signal when applying CO_2 (a) and CO (b) with (dotted line) and without (solid line) gas lock filters; (●) are for experimental values.

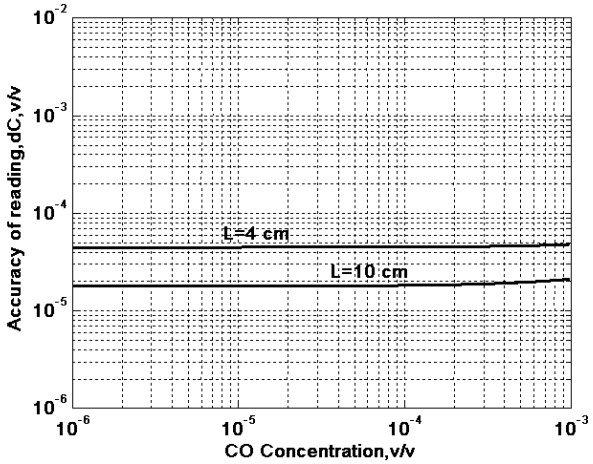


Fig.9. Accuracy of CO sensor readings for immersion lens diode sensor A-function with $\lambda_{max}(20^0C)$=4.65 μm.

4. RESULTS AND CONCLUSIONS

The analytical model of an optical gas sensor based on mid-IR diode optopairs that permits calculating its transfer function and estimating the expected accuracy of measurements and temperature stability of readouts has been developed.

The spectral characteristics of immersion optopairs in the 3.3, 4.3 and 4.7 μm range were studied. These characteristics allowed us to calculate the instrument functions and to determine the spectral and temperature properties for the sensors of hydrocarbons, carbon dioxide and carbon monoxide.

The results of studying the optical sensors of carbon dioxide (CO_2), hydrocarbons (by the example of ethylene C_2H_4) and carbon monoxide (CO) are presented. Good matching of the calculated and experimental data proves the validity of the proposed model. The presented results indicate the promising use of the immersion diode optopairs and portable gas analysers: the expected values of threshold sensitivity (LOD) correspond to the level 50-100 ppm for the above-mentioned gases at the operational speed equal to several seconds and small (less than 10 ml) volumes of a gas cell meet the requirements of most practical applications of a portable equipment for gas analysis.

The developed analytical model is a useful instrument for the initial stage of designing different-purpose optical gas sensors.

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