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Study of a computer-controlled integrated optical gas-concentration sensor

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***Abstract*.** **A computer-controlled integrated optical waveguide sensor based on an optical waveguide of the diffusion type with the low attenuation coefficient is developed and studied. It is shown that the response time of the sensor is ~ 0.15 s. According to tests and computer simulations, the sensor can detect gaseous ammonia in air with the limiting theoretical concentration of ~ 0.1 ppm for the signal-to-noise ratio no less than 20.**

Keywords: *integrated optical sensor, laser radiation, air contaminants, environment monitoring.*

1. Introduction

The detection of CO, NO_x, NH_3, and SO_x gases is an important problem in the fields of physical ecology, environment monitoring, medicine, chemistry, and military technologies. There exist different types of sensors [1 – 4] based on different physical or chemical effects and properties of materials.

The development of sensors for measuring the temperature, pressure, humidity, and concentration of gases is stimulated, in particular, by the necessity to improve devices for environment monitoring and by progress in physical ecology. The development of such devices is closely related to the advent of new types of sensors – optical sensors. Interest in the development and application of these sensors is caused by a number of their advantages over non-optical sensors such as the high sensitivity, fast response, the possibility of using for remote sensing, the simplicity of signal multiplexing, and the possibility of using integral technologies for their manufacturing. Integrated optical sensors are, in our opinion, the most promising among optical sensors [1 – 3, 5 – 8].

The operation principle of integrated optical sensors of the absorption type is based on the recording variations in the laser radiation intensity propagating through gaseous (gas, vapour) or liquid media (located near the sensor) at some wavelengths typical for the medium under study. The main problem is to develop simple in operation, compact, accurate, and safe sensors with a fast response for measuring, for example, concentrations of various gases in the atmosphere, especially at extremely low concentrations.

In this paper, we propose to improve the parameters of an integrated optical sensor (sensitivity, response time, etc.) by using a miniature electronic comparison circuit based on precision operational amplifiers, analogue-to-digital signal transformation, and computer storage and processing of digitised data.

2. Computer-controlled integrated optical sensor

The efficiency of an integrated optical sensor was demonstrated by using a model based on a diffusion waveguide. Figure 1 presents the scheme for detecting gaseous ammonia by means of this sensor. The waveguide was fabricated by the method of solid-state diffusion of PbO_2 into a K8 glass plate (the 14th class of surface processing purity). Radiation was coupled in and coupled out through a TF5 glass prism with the refractive index $n = 1.7497$ at 632.8 nm.

Figure 2 shows the general scheme of the experimental setup. The source of coherent radiation was He – Ne laser (*1*) emitting at a wavelength of 632.8 nm falling into one of

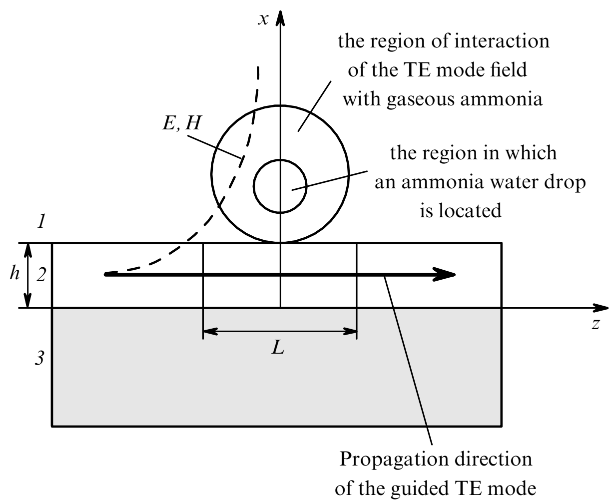

Figure 1. Scheme for detecting gaseous ammonia: (*1 – 3*) integrated optical waveguide [(*1*): air layer; (*2*): waveguide layer; (*3*): substrate]; (*h*) waveguide layer thickness; (*L*) distance between the input and output prisms (waveguide cell length). The exponential decay of the electromagnetic field strength of the guided TE mode in air is shown schematically.

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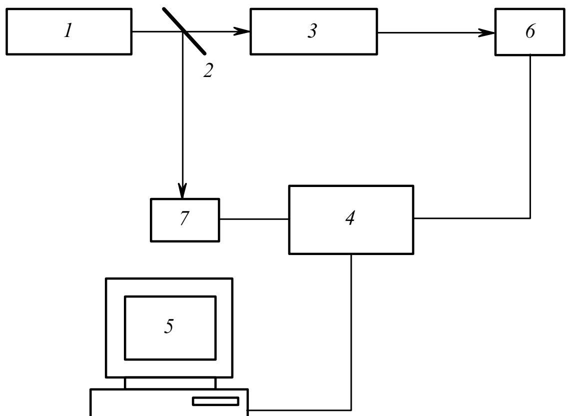

Figure 2. Scheme of the experimental setup: (*1*) helium–neon laser; (*2*) beamsplitter; (*3*) waveguide sensor cell; (*4*) electronic comparison circuit; (*5*) computer; (*6, 7*) photodetectors.

the absorption bands of ammonia.

The laser beam was split in beamsplitter (*2*) into the reference and probe beams. The probe beam was coupled into optical waveguide (*3*) through the input prism at an angle corresponding to resonance excitation of the TE_0 mode. The coupling efficiency η of the He–Ne laser radiation into the diffusion waveguide was about 40 %. The radiation coupled into the waveguide propagated in it, partially penetrating into the upper cover medium, and a decrease in the signal amplitude was observed at the output of the prism in the presence of gas under study, which was detected with photodetector (*6*).

The reference beam was detected with second photodetector (*7*). Photodetectors were PD-256 photodiodes. The output signals of photodetectors were fed to electronic comparison circuit (*4*), subjected to the analogue-to-digital transformation, and recorded and processed in computer (*5*).

Comparison circuit (*4*) uses precision operational amplifiers with a small bias voltage and a high voltage gain.

The experimental results were recorded digitally by using a computer-controlled virtual PC-LAB 2000 laboratory, whose possibilities can be expanded by means of the mathematical processing of experimental data. The text file contained the experimental data such as the time step (0.5 s), vertical scale (5 mV), numbers of points and other data.

The obtained data can be processed by using simple programs of the Basic type or program complexes based on MathCAD, Maple, Mathematica or Mathlab computational programs. Graphic packages such as Microcal Origin can be also used. The advantages of the latter program are, for example, the possibility of the spectral estimate, spline interpolation, polynomial approximation, dispersion analysis, and the calculation of the correlation coefficient and cross-correlation function. All this opens up wide prospects for mathematical and computer processing of experimental data.

The signal-to-noise ratio in measurements was, on average, no less than 15. The response time of the computer-controlled integrated optical sensor did not exceed 0.15 s (Fig. 3); the sensor rapidly enough (for ~ 0.3 s) returned to the initial state and was again ready for operation.

3. Results of testing the computer-controlled optical sensor and discussion

Figure 3 shows the results of testing the computer-controlled integrated optical sensor. We used in experiments specially prepared and preliminarily investigated diffusion waveguides with high operation parameters. A diffusion waveguide had the effective refractive index $n_{\text{eff}} = 1.521$ for the TE_0 mode. Losses measured by the known method of detecting the radiation power at the input and output of the waveguide did not exceed 0.1 cm^{-1}. The distance between the input and output prisms was $L = 4$ cm. The width of the laser beam path in the waveguide was 0.1 cm.

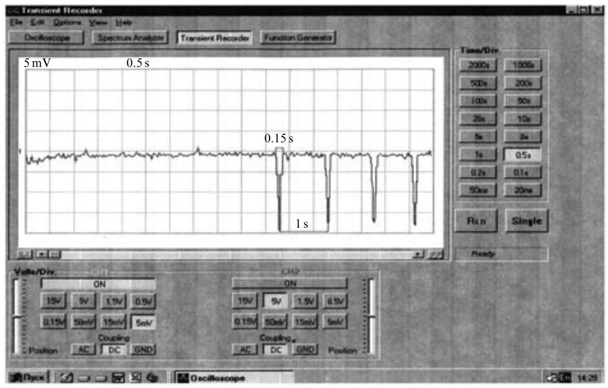

Figure 3. Results of testing of the computer-controlled integrated optical sensor.

At a distance of 1 cm from the waveguide layer doped with PbO_2, a dropping tube containing the 10 % solution of ammonia water (aqua ammonia) was placed. Drops of diameter $d = 0.3$ cm flied at 1-s intervals through the laser beam path in the waveguide, where the field of the waveguide TE_0 mode interacted with gaseous ammonia.

The output signal of the electronic comparison circuit was fed to a visualisation device. Figure 3 demonstrates signals from gaseous ammonia displayed on a monitor screen. This figure illustrates good repeatability of measurements at the same concentration of NH_3. Indeed, the root-mean-square deviation of voltage at the moments of detecting gaseous ammonia from the root-mean-square value did not exceed 5 %.

The estimate showed that the concentration of gaseous ammonia in experiments was 4 ppm. Calculations were performed by using the Bouguer–Lambert–Beer law in the integral form

$$P = P_0 \exp\left[-\int_{-L/2}^{L/2} \sigma N(z)\,\mathrm{d}z\right], \tag{1}$$

where P and P_0 are the laser radiation power at the output of the waveguide cell in the presence and absence of ammonia, respectively; L is the thickness of the medium under study (the absorption cell length); $N(z)$ and σ are the distribution of the ammonia concentration along the z axis and its absorption cross section, respectively; and $\sigma N(z) = \alpha(z)$ is the local attenuation coefficient of the guided laser radiation mode in gaseous ammonia.

The attenuation coefficient of laser radiation in gaseous ammonia was measured to be ~ 0.04 cm^{-1}. Knowing the absorption cross section of ammonia $\sigma \approx 3.8 \times 10^{-16}$ cm^2 at the He–Ne laser wavelength 632.8 nm, we find the concentration of ammonia $N \approx 1.1 \times 10^{14}$ cm^{-3}, which corresponds to the relative volume concentration of gaseous ammonia in air of $\sim 4 \times 10^{-4}$ % (or 4 ppm).

The concentration distribution $N(z)$ was found by solving the auxiliary inverse problem by using the model of Gaussian turbulent diffusion (see, for example, [9]) of gaseous ammonia in air. This problem will be analysed in detail elsewhere. Note here only that for the known parameters of the problem (the sensor cell length, the attenuation coefficient of the guided mode, the distance from the gaseous ammonia source to the guided mode path, etc.), a Gaussian function approximating $N(z)$ was selected. It was also taken into account that the diffusion relaxation time τ of the ammonium concentration in air was approximately 0.5 s ($\tau \approx d^2/D$, where D is the diffusion coefficient of ammonium) and the sensor response time did not exceed 0.15 s. The signal-to-noise ratio in the measurements was, on average, no less than 15. The total time of the analysis, i.e. the time after which the sensor was again ready for functioning, was no more than 0.3 s, which is better than for models described, for example, in [5, 7].

Figure 4 shows some experimental data processed by using the graphic Microcal Origin package. The filtration technique with the use of the fast Fourier transform (FFT) is well known and does not require a detailed description. The FFT performs fast data transfer from the time to frequency domain, where the high-frequency noise component is suppressed. Then, the filtered signal is returned to the time domain by using the inverse FFT. The application of FTT with the efficient noise filtration can be very useful in measurements at the sensitivity limit of the integrated optical sensor. An important property of the FTT algorithm is that the number of counts in the frequency domain is smaller by half than that in the time domain. This reduces the time of computer calculations, which is especially important in the case of large computational volumes.

Computer calculations showed that the sensitivity of this sensor was an order of magnitude better than that of similar sensors without the use of the precision electronic comparison circuit and subsequent data processing.

Figure 5 presets the dependence of the minimal attenuation coefficient $\alpha_{min}(z)$ of the waveguide caused by the presence of gaseous ammonia. This dependence characterises the minimal sensitivity of the integrated optical sensor. The attenuation coefficient for the guided mode in the presence of random noise of power P_n was calculated with a computer from the known relation

$$\alpha_{min}(z) = \ln[(P_0 + P_n)P_{min}^{-1}]z^{-1}, \qquad (2)$$

where P_{min} is the signal power at which the signal-to-noise ratio, on average (from realisation to realisation of the random noise) is no less than 20. Figure 5 also shows that to achieve a sensitivity level of 0.1 ppm, the sensor cell length should be no less than 4 cm. Computer simulations showed that the sensitivity of this sensor can be further increased by increasing, for example, the efficiency η of coupling laser radiation to the waveguide and reducing losses caused by scattering of light from irregularities of the waveguide part of the sensor at fixed η.

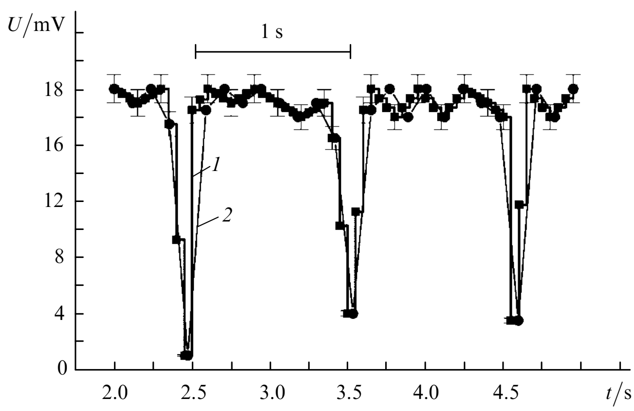

Figure 4. Interpolation of sampled experimental data (*1*) and smoothing of these data with the help of a low-frequency filter by using the FFT (*2*). The measurement error was 5 %.

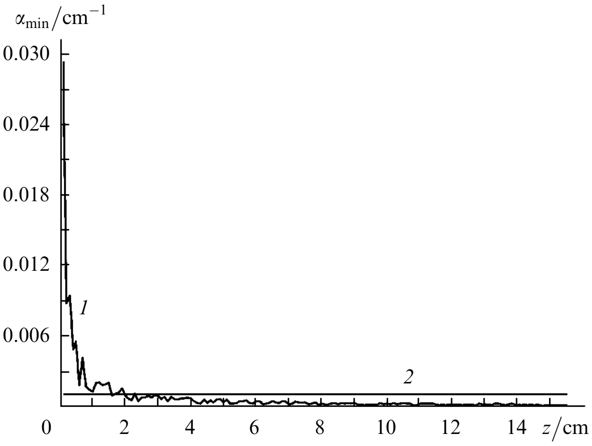

Figure 5. Dependence of the minimal sensitivity α_{min} of the integrated optical sensor on the sensor cell length L (it is assumed that $L = z$) for the signal-to-noise ratio no less than 20 (*1*) and the level $\alpha_{min}(z) = 1.03 \times 10^{-3}$ cm^{-1} corresponding to the concentration of gaseous ammonia in air equal to 0.1 ppm (2).

We do not analyse here the scattering of light in an 'irregular' waveguide because this problem was discussed in detail in the literature (see, for example, [4, 10–13]). It follows from the results obtained that such scattering is one of the most important factors restricting the achievement of the limiting sensitivity if the noise level (external illumination at the laser wavelength, photodetector and device noises) is low or if a special detection method is used which provides the signal-to-noise ratio no less than 20.

Thus, the results of testing show that the sensitivity of the integrated optical sensor used in a computer-controlled device containing an electronic comparison circuit can be considerably increased compared to usual integrated optical sensors in which analogue signals are detected, for example, by a digital voltmeter.

We used a diffusion waveguide in experiments because it has low losses and stable characteristics at specified technological parameters. Despite a small fraction of the guided mode power propagating in a detected gaseous medium (gas, vapour)*, we have chosen namely a diffusion wave-

*It is known that the concepts of gas and vapour are almost completely equivalent ([14], p. 527). However, it seems that the study of the dynamics of phase transitions, critical opalescence, and other phenomena requires the specification of the state of gaseous ammonia.

guide for the working model of the sensor because at this stage of investigations we paid the main attention to fundamentally important problems of signal detecting and processing in the presence of noises.

Note that to increase the fraction of the guided mode power in a detected medium, it is necessary to use films with a high refractive index or a thin layer on the waveguide surface with optimised parameters [8].

The sensitivity of the integrated optical sensor can be further increased by different methods, in particular [1 – 3, 8]:

(i) by increasing the sensor cell length (for example, by using a substrate in the form of a cylindrical rod, Bragg reflectors, resonators, etc.) [1];

(ii) by optimising the parameters of the waveguide system [8];

(iii) by increasing the signal-to-noise ratio;

(iv) by integrating the elements of the sensor including the radiation source, the sensor cell and photodetector on a single substrate.

The high sensitivity and fast response of the integrated optical sensor were achieved by using low-attenuation diffusion waveguides, the noise-suppressing miniature electronic comparison circuit based on precision operational amplifiers, and computer data storage and processing.

The signal-to-noise ratio can be increased, first, by optimising the parameters of the electronic comparison circuit and, second, by decreasing losses in the waveguide system caused by laser radiation scattering, in particular, by using substrates with weakly rough surfaces.

Computer simulations have shown that the minimal concentration of gaseous ammonia, which can be measured with a sensor of this type, is ~ 0.1 pm for the signal-to-noise ratio ~ 20 and a distance from the ammonia source to the waveguide surface of 10 – 20 cm.

4. Conclusions

We have studied the computer-controlled diffusion integrated optical ammonia sensor. The sensor uses noise-suppressing miniature electronic comparison circuit based on precision operational amplifiers and computer data storage and processing and features good metrological parameters. Sensors of this type are simple to fabricate, test, and adjust. The theoretical value of the threshold ammonia concentration measured by this sensor can be lower than 0.1 ppm for the signal-to-noise ratio ~ 20.

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