

ABSTRACT

to the dissertation work submitted for the degree of Doctor
of Philosophy (PhD) in the educational program «8D06201–Radioengineering,
electronics and telecommunications»

TILEU AYAN

CONCENTRATION SATURATION OF THE SIGNAL FROM A LASER GAS SENSOR

General characteristics of the work. The dissertation research is devoted to the investigation of the operating characteristics of gas sensor systems based on the laser absorption method. The mechanisms of laser gas sensor signal formation, its fluctuation properties, and the phenomenon of concentration saturation under varying concentrations of methane, ethanol, and ammonia were studied both experimentally and theoretically. During the research, optical processes arising from the interaction of laser radiation with gas molecules in a closed gas cell were analyzed, along with the electrical signal recorded by the photodetector after the radiation passed through the gas medium. Linear and nonlinear regimes of the sensor signal dependence on gas concentration, as well as the conditions for transition into the saturation region, were determined. The relationship between the absorption intensity of laser radiation and the thermal motion of gas molecules with increasing gas concentration was described using the fluctuation–dissipation relation and correlation functions. In addition, methods based on Shannon entropy were applied to evaluate the informational properties of the sensor signal. The obtained results have practical significance for optimizing the operating range of laser gas sensors, correctly selecting the linear operating region of the sensor, and ensuring reliable identification of gas concentration and gas type.

Research Relevance. At the present stage, the rapid development of industrial technologies, increasing requirements for environmental safety, and the growing importance of protecting human health have significantly increased the demand for sensor systems capable of continuous and highly accurate monitoring of gas composition in the environment. In particular, the rapid detection of low concentrations of flammable, toxic, and hazardous gases is critically important for industrial safety, environmental monitoring, energy systems, and the residential sector.

Currently, various types of sensors based on different operating principles are used to analyze gas media composition. Among them, laser gas sensors are distinguished by their high sensitivity, capability for non-contact measurements, and selectivity toward specific gas species. Since laser methods are based on the absorption characteristics of gas molecules, they provide high accuracy and reliability of measurement results. However, with increasing gas concentration, the laser sensor signal transitions from a linear regime to a nonlinear regime, accompanied by the appearance of saturation effects, which significantly limits measurement accuracy.

The concentration saturation of the sensor signal is associated with complex fluctuation and nonlinear processes occurring during the interaction between gas molecules and laser radiation. Understanding the physical mechanisms of this phenomenon, determining saturation thresholds, and correctly selecting the operating range of the sensor for different gases constitute important scientific and technical challenges in the practical application of laser gas sensors. In particular, investigating the saturation characteristics of sensor signals for gases widely used in industry and everyday life, such as methane, ethanol, and ammonia, is of great relevance.

As gas concentration increases, the absorption intensity of laser radiation, the fluctuations of the signal recorded by the photodetector, and their correlation properties undergo significant changes. The analysis of these changes using the fluctuation–dissipation relation, correlation functions, and information-entropy-based methods makes it possible to achieve a deeper understanding of the sensor signal formation mechanisms. In addition, the application of universal functional dependencies based on scale invariance provides new approaches for estimating sensor signal saturation concentrations.

Thus, investigating the mechanisms of concentration saturation in laser gas sensor signals, determining their fluctuation and informational characteristics, and establishing saturation thresholds for different gases constitute an important and relevant scientific problem in the development of modern sensor systems intended for accurate gas concentration measurements.

Research Objective. The objective of this research is the experimental and theoretical investigation of concentration-dependent saturation mechanisms in the signals of gas sensors based on the laser absorption method, determination of sensor signal saturation thresholds for methane, ethanol, and ammonia, as well as the characterization of linear and nonlinear operating regimes of the sensor using fluctuation–dissipation and information-entropy-based methods.

The object of the research. Nanoscale porous silicon (PS), CuO/PS structures, a laser source, a gas cell, a photodetector, and a digital data acquisition system;

The subject of the research. The concentration-dependent variation of the laser gas sensor signal, as well as its fluctuation, correlation, and information characteristics.

Research methods. The research methods included laser absorption measurements, digital acquisition and processing of photodetector signals, fluctuation–dissipation, correlation, and information-entropy analyses, as well as experimental and analytical approaches.

In order to achieve the above stated goal, it is necessary to carry out the following tasks:

1. To design and assemble an experimental gas sensing system based on the laser absorption method and perform measurements with methane, ethanol, and ammonia gases in a closed gas cell;
2. To acquire time-series data of the laser sensor signal registered by the photodetector as a function of gas concentration and to digitize these data;
3. To analyze the linear and nonlinear operating regimes of the sensor signal using fluctuation–dissipation relations and information-entropy methods;

Scientific novelty of the dissertation results.

The novelty and originality of the work are as follows:

1. The physical mechanism of concentration saturation in laser gas sensor signals was comprehensively investigated in terms of fluctuation processes arising from the interaction between photons and gas molecules;
2. The saturation concentrations of laser sensor signals for methane, ethanol, and ammonia gases were experimentally determined, and their relationship with fluctuation–dissipation and information characteristics was established;
3. For the first time, the behavior of correlation functions and Shannon entropy in the saturation regime was comparatively analyzed, and information-based criteria for distinguishing linear and nonlinear operating regions were proposed;

The main provisions for the defense.

1. A nanostructured sensor based on CuO/PS, in terms of gas sensitivity characteristics under a constant voltage, demonstrates a 20% increase in current within 1–3 minutes.
2. The concentration saturation of the laser sensor signal for various gases is determined by the fluctuation–dissipation theorem. In this case, the saturation concentration values for different gases are: $C_*(\text{NH}_3) = 10^2$ ppm, $C_*(\text{C}_2\text{H}_5\text{OH}) = 10^3$ ppm, $C_*(\text{CH}_4) = 10^4$ ppm.
3. The self-similar information $I_*=0.567$ and the self-similar entropy $H_*=0.806$ determine the coherence coefficient of the laser gas sensor signal: $\eta = (H_* - I_*)/(H_* + I_*) \approx 0,174$.

Theoretical Significance of the Research. The results obtained in this dissertation are aimed at explaining the physical nature of the concentration-dependent saturation phenomenon in the signals of gas sensors based on the laser absorption method. The analysis of the interaction process between gas molecules and laser radiation from the standpoint of fluctuation–dissipation and information-entropy approaches makes it possible to theoretically describe the linear and nonlinear operating regimes of the sensor signal. The obtained theoretical conclusions may serve as a basis for further development of models for investigating the fluctuation and correlation properties of laser gas sensor signals.

Practical Significance of the Research. The practical significance of the work is determined by the possibility of optimizing the operating range of laser gas sensors and improving measurement algorithms that take into account the concentration saturation regime of the signal. The experimentally determined saturation concentrations can be used in the design of sensor systems intended for highly accurate detection of methane, ethanol, and ammonia. The obtained results are aimed at improving the accuracy and reliability of laser gas sensors used in environmental monitoring, industrial safety, energy systems, and gas monitoring applications.

Reliability and Validity of the Obtained Results. The reliability and validity of the dissertation results are confirmed by publications in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as in journals indexed in the international scientific databases Web of Science (Clarivate Analytics,

USA) and Scopus (Elsevier, Netherlands), publications in proceedings of international scientific conferences, and consistency with the results obtained by other researchers.

Author's Contribution. The author independently carried out all stages of the dissertation research. The author personally developed the experimental gas sensor system based on the laser absorption method, performed measurements using methane, ethanol, and ammonia in a closed gas cell, obtained time series of sensor signals recorded by the photodetector, and conducted their digital acquisition.

The analysis of fluctuation, correlation, and information-entropy characteristics of the sensor signal, determination of concentration-dependent linear and nonlinear regimes, and evaluation of signal saturation thresholds were performed with the direct participation of the author. Processing, interpretation, and generalization of the research results were also carried out by the author.

The clarification of the research objectives and tasks, approval of the research plan, and discussion of the obtained results were conducted jointly with the scientific supervisor.

Approbation of the Work. The results of the dissertation research were published in the following sources:

Articles published in journals indexed in the international scientific databases Thomson Reuters and Scopus:

1. Khaniyev B., Ibraimov M., Nalibayev E., Skabylov A., Khaniyeva A., Jianxi L., Tezekbay Y., Duisebayev T., **Tileu A.**, Meirambekuly N. Development of cupric oxide/porous silicon (CuO/PS) heterostructure enabled room temperature methane sensor for enhanced industrial safety // Engineered Science. – 2024, 31, 1268. **Scopus: CiteScore 12.5, Percentile 96%. Q1.** <http://dx.doi.org/10.30919/es1268>

Articles published in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan:

1. Zhanabaev Z., Akhtanov S., Tileu A., Almen D. Coherent amplitude modulation in a laser gas sensor. Eurasian Physical Technical Journal, 2023, Vol. 20, № 4 (46), pp. 111–115. Scopus: CiteScore 1.2, Percentile 26%, Q3. <https://doi.org/10.31489/2023No4/111-115>

2. Zhanabaev Z., Tileu A., Duisebayev T., Almen D. Saturation of gas concentration signal of the laser gas sensor. Eurasian Physical Technical Journal, 2024, Vol. 21, № 3 (49), pp. 71–80. Scopus: CiteScore 1.2, Percentile 26%, Q3. <https://doi.org/10.31489/2024No3/71-80>

Publications in International Conference Proceedings

1. Tileu A.O. Gas type discrimination using a laser sensor. Proceedings of the International Scientific Conference of Students and Young Scientists “FARABI ALEMI”, 2023, p. 187.

2. Tileu A.O., Akhmetova M.A. Determination of Allan variance for low-frequency fluctuation signals in a laser gas sensor. Proceedings of the International

Scientific Conference of Students and Young Scientists “FARABI ALEMI”, 2024, p. 207.

3. Tileu A.O., Sazbay A.M. Coherence of the laser gas sensor signal. Proceedings of the International Scientific Conference of Students and Young Scientists “FARABI ALEMI”, 2025, p. 223.

Certificate of copyright

1. Zhanabayev Z.Zh., Ibraimov M.K., Akhtanov S.N., Khaniyev B.A., Tileu A.O., Namazbayev T.A., Meirambekuly N., Duysebaev T.S. Device for modulation coherence of a laser gas sensor signal // Utility Model Patent, 2025, № 9374.

The scope and structure of the thesis.

The dissertation consists of an introduction, three chapters, a conclusion, and a list of references. The work contains 63 figures, 56 equations, 1 table, 92 references, and comprises 100 pages.