

Brief information about the project

Name of the project	AP26102313 «Coherence and saturation of laser sensor signals»
Relevance	The relevance of this project is driven by the need to develop new highly sensitive and reliable methods for detecting and analyzing gaseous media, which are crucial for ensuring industrial and environmental safety, including the prevention of explosions, fires, and toxic exposures. Conventional spectroscopic methods for gas analysis have limited sensitivity and do not adequately account for nonlinear, fluctuation-driven, and chaotic operating regimes of laser sensors. In this context, the application of modern information-entropy and fluctuation-dissipation approaches becomes particularly important, as they enable a more accurate description of self-organization, coherence, and saturation processes in laser sensor signals. Despite existing studies in this field, the physical nature of fluctuation signals and their relationship with gas concentration remain insufficiently understood. The proposed project aims to address this gap by developing new digital signal processing methods and experimental approaches, thereby improving the accuracy of gas identification and expanding the practical applicability of laser sensor systems.
Purpose	The purpose of this project is to create a new theoretical model for determining the type of gas and its saturation concentration before shutting down production using a laser radiation signal. Conducting physical experiments, creating sensor samples with digital IoT technology for recommendation for production.
Objectives	The following main objectives are set: 1) Determine the correlation functions by frequency and wave number (using the Lorentz spectrum in sensor physics and the Cauchy formula in mathematics) for the output voltage of a laser gas sensor based on the Einstein-Smoluchowski equation with random force. 2) Represent the Lorentz spectrum in a form depending on the ratio of the target gas concentration to its value when the photon energy is equal to the thermal energy of the oscillation quantum (C/C_*). 3) Determine the coherence modes ($C < C_*$) and saturation ($C > C_*$) for the laser sensor signals for gases with different symmetries of their molecular structure (methane, ammonia, ethanol). 4) Experimental results of the response of a semiconductor photodiode to the passage of a laser beam through gases of different concentrations. 5) Obtaining the Lorentz spectrum near the fundamental frequency, which occurs in the presence of fluctuations in the experimental data due to bifurcations of doubling the

	period of the signal from the network power supply of the device. 6) Determining the values of the conditional information of the quantitative criterion of coherence and contrast of the experimental signal of the sensor. 7) Determining the values of the dissipation function $th(2C/C_*)$ for the experimental modes of coherence ($C < C_*$) and saturation ($C < C_*$). 8) Algorithms of digital technology and hardware implementation of wireless transmission via IOT of the values of $th(2C/C_*)$ to the analysis center. 9) Provide recommendations for optimal parameter values for the production sample of the laser gas sensor and facilitate patent registration.
Expected and achieved results	Expected Results: For 2025: An analytical formula describing the dependence of the Lorentzian power spectrum on frequency and spectral linewidth will be derived. The dependence of the Lorentzian spectrum on the normalized concentration C/C_* will be established, where C_* corresponds to the condition of equality between photon energy and thermal energy. Graphs of the dissipation function will be constructed for the cases $C < C_*$ and $C \geq C_*$, reflecting the transition between thermal and coherent regimes in a gaseous medium. For 2026: Experimental graphs of variance, correlations, and fluctuation-induced voltages will be obtained for various gases, taking into account their molecular structure. Bifurcation values of concentration C_* will be determined both experimentally and theoretically for gases with different molecular configurations. Normalized values of conditional information for the coherent state will be calculated based on experimental data, enabling a quantitative assessment of the degree of signal ordering. For 2027: Graphs of the function $\tanh(2C/C_*)$ will be constructed based on theoretical models and experimental data for the regimes $C < C_*$ and $C \geq C_*$. Algorithms and techniques for wireless transmission of the results of the function $\tanh(2C/C_*)$ will be developed using IoT technologies, including applications for various gas mixtures. Scientific publications will be prepared and submitted, patent applications (including utility models) will be filed, and recommendations for the implementation of the obtained results into industrial processes will be developed. Achieved Results for 2025: An analytical formula describing the dependence of the Lorentzian power spectrum on frequency and spectral linewidth was obtained. As a result of the theoretical analysis of the fluctuation–dissipation relation, an analytical form of the fluctuation power spectrum near the fundamental

frequency ω_0 was derived, taking into account photon absorption by the gaseous medium. The Lorentzian spectrum formula was obtained as a function of frequency ω and spectral linewidth, allowing the energy structure of fluctuations to be described in the regime of weak absorption and under the condition $\hbar\omega_0 \ll 2kT$. The obtained dependence is used as a baseline model for subsequent stages of saturation analysis.

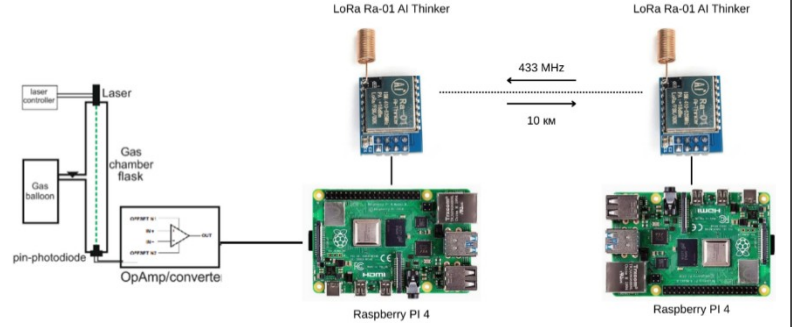


Figure 1. Block diagram of sensor data transmission over a distance

The dependence of the Lorentzian spectrum on C/C_* was established, where C_* is the gas concentration at which photon energy equals the thermal energy of the medium. Based on a simplified form of the fluctuation–dissipation relation, the dependence of the normalized spectral intensity on the ratio of the current gas concentration C to the critical concentration C_* was derived. It was shown that the sensor spectral response is described by the function

$$I(\omega) |_{I_{max}} = \tanh\left(\frac{2C}{C_*}\right),$$

which reflects the transition of the system from the transparent regime (low concentrations) to the saturation region (high concentrations). The parameter C_* was determined theoretically through quantum and thermal characteristics of the gas, providing a physically justified normalization of the measured signal.

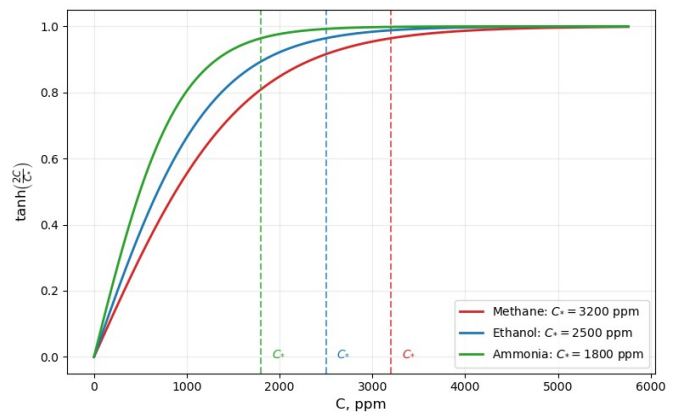


Figure 2. Theoretical saturation model for methane, ammonia, and ethanol gases

	Graphs of the dissipation function for the cases $C < C_*$ and $C \geq C_*$ were obtained. Based on the dissipation function $\tanh(2C/C_*)$, theoretical curves describing the behavior of the gas sensor before saturation and at saturation were constructed. In the range $C < C_*$, a linear-sigmoidal dependence with a gradual increase in response was observed, characteristic of the transparency-dominated regime. In the region $C \geq C_*$, pronounced nonlinearity and signal saturation were obtained, consistent with physical processes of dominant photon absorption by gas molecules. The constructed graphs were used to verify experimental data and to calibrate the concentration analysis algorithm.
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Usage	Laser sensors and methods for analyzing fluctuation signals are applicable to industrial monitoring of gaseous environments, control of hazardous gas concentrations, prevention of emergency situations (such as explosions, fires, and toxic exposures), as well as to scientific investigations of physical processes in gas systems.
Priority compared to real-world alternatives	The proposed project demonstrates several significant advantages compared to existing analogues in the field of gas sensing systems. While conventional approaches are primarily based on optical spectroscopy and the Beer–Lambert–Bouguer law, this project introduces a fundamentally new approach based on the analysis of fluctuation signals using information-entropy and fluctuation–dissipation methods. One of the key advantages is the use of a normalized dependence of spectral intensity on the concentration ratio C/C_*, which enables physically justified sensor calibration without altering the geometric parameters of the measurement system. In contrast to existing analogues, the proposed method allows for the identification of transition regimes between coherent and saturation states, significantly improving measurement accuracy and sensitivity, especially at low concentrations.

	An additional advantage is the consideration of nonlinear, chaotic, and bifurcation effects in the sensor signal, which are typically neglected in conventional approaches. This enables a more comprehensive description of the physical nature of laser radiation interaction with a gaseous medium and expands the diagnostic capabilities of the method. Furthermore, the project includes real-time digital signal processing and integration with IoT technologies for remote data transmission and analysis, thereby enhancing monitoring efficiency and broadening the scope of practical applications. Thus, the proposed approach ensures higher informativeness, accuracy, and versatility compared to existing solutions and provides a scientific and technological foundation for the development of next-generation laser gas sensors.
List of publications with links to them	Zhanabaev Z., Akniyazova A., Ashimov Y. Information–Entropy Analysis of Stellar Evolutionary Stages with Application to FS CMa Objects //Entropy. – 2025. – V. 27. – No. 11. – p. 1106. https://doi.org/10.3390/e27111106
Patents	A utility model patent application has been submitted to the National Institute of Intellectual Property of the Republic of Kazakhstan: «Algorithm for implementing IoT technology for remote transmission of gas sensor signal saturation as a function of increasing concentration» Incoming No. 2025-92971 dated 26.11.2025 Barcode No. 3756112