OPTICAL HUMIDITY SENSOR WITH DIFFERENTIAL REGISTRATION

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Abstract.

The article discusses the development of a fiber-optic moisture sensor based on differential registration. The possibility of a sharp increase in the sensitivity of a fiber sensor due to the transition to the method of laser absorption with an internal resonator is analyzed. The change in the laser emission spectrum due to selective absorption and the scheme of a laser spectrometer with an internal resonator are presented. The block diagram and main technical parameters of a fiber-optic sensor using a differential registration scheme and an active fiber ring laser design are presented.

Key words:

Differential, resonance, optical fiber, laser, quantum generator, spectrum, intensity, sensor.

The emergence and development of laser technology led to the creation of a new version of absorption analysis – intracavity laser absorption (ICLA). The first works in which the features in the generation spectrum of optical quantum generators were explained by the presence of selective absorption by the medium inside the cavity appeared in the early 1970s. [1-2]. Determination of the positions of the dips in the lasing spectrum of the laser makes it possible to identify them with a certain type of absorbing atoms or molecules, i.e. carry out a qualitative analysis of the gas placed inside the resonator. Measuring the size and shape of the dips allows, ultimately, determining the number of absorbing particles. Placing a cell with a gas inside the laser cavity, the absorption lines of which fall into the lasing region, leads to a change in the nature of the spectrum or the integral intensity of the laser radiation. If a gas with relatively narrow absorption lines γ_1, γ_2, γ_3 (Fig.1) is placed in the cavity of a multimode laser with a wide lasing line $\Delta\gamma$, then dips in the radiation intensity will be observed in the lasing spectrum at frequencies γ_1, γ_2, and γ_3. The formation of these dips is due to the fact that the introduction of additional selective losses leads to a redistribution of the radiation intensity of the generated modes and to the “burnout” of modes that coincide in frequency with the absorption lines of the gas under study, i.e. The modes generated by a broadband laser that coincide in frequency with the absorption lines of the gas experience, as it were, double suppression, both due to the direct absorption of radiation by the gas mixture placed inside the cavity and due to competition between the laser modes.

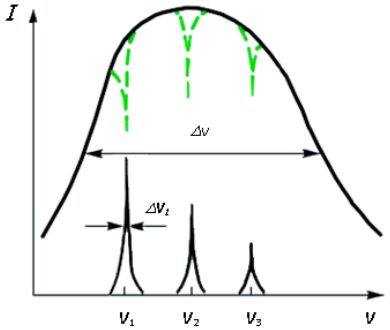

Figure 1 – Changing the laser generation spectrum due to selective absorption

If the width of the gas absorption line is equal to or greater than the width of the laser generation line, the radiation intensity decreases until the generation is disrupted by changing the Q-factor of the resonator in the generated mode. This method is adequate for absorption in a multi-pass cell outside the resonator, but with a significant increase in the effective thickness of the absorbing gas layer, since the loss in radiation intensity when reflected from the mirror surface is largely compensated by the gain in the active laser medium.

The "narrow-band" version of the method has a better resolution compared to the "broadband" one, which is determined by the width of the laser radiation line, so its analytical application is preferable when solving problems of analyzing complex mixtures, when the main one is the resolution of superimposed components in the absorption spectra of various molecules.

When solving the problems of determining micro-impurities, it is more justified to use a "broadband" version of the method, which is more sensitive to small selective losses inside the resonator due to the additional influence of competition of the generated modes and has greater generation stability, since it works in conditions of a significant excess over the generation threshold.

The possibility of radically increasing the sensitivity of the fiber sensor by switching to the method of intracavity laser absorption. The main question that arises when considering the possibility of using a particular method for solving analytical problems is the possibility of an unambiguous and simple connection of the measured analytical signal with the content of the determined component. In the method of ICLA up to the present time there are difficulties in obtaining quantitative information about the concentration of absorbing particles. This is due to the fact that the measured change in the intensity of laser radiation at frequencies that coincide with the absorption lines of the analyzed gas (i.e., the depth and shape of dips in the generation spectrum) depend on both the parameters of the absorption lines and the laser parameters.

Assuming that the width of the absorption line $\Delta\gamma_i$ is much smaller than the width of the laser radiation spectrum $\Delta\gamma$ and the registration time t does not exceed the time of continuous laser generation T_c, when the generating modes can be considered independent, the intensity of the laser radiation spectrum $I(\gamma, t)$ in the region of the absorption line is described by the expression [3]:

$$I(\gamma, t)=I(\gamma,0)\exp[-k(\gamma)(ct\, L_G / L_R)], \quad (1)$$

where $I(\gamma, 0)$ is the laser radiation intensity at the beginning of generation; $k(\gamma)$ is the spectral absorption coefficient; t is the registration time; L_G and L_R are the lengths of the absorbing gas layer and the laser resonator.

Expression (1) allows us to find the spectral absorption coefficient by either measuring the instantaneous values of the generation intensity at frequencies γ_1, γ_2, γ_3, at times t_1, t_2 (in this case, $\Delta t=t_2 - t_1$ should be less than the time of continuous generation of the *Tn* mode), or by integrating the change in $I(\gamma_1, \gamma_2, \gamma_3)$ during the observation time In the first case, the values of $k(\gamma)$ are found from the expression:

$$k(\gamma)= -(L_R / cL_G\, \Delta t)\ln I(\gamma, \Delta t), \quad (2)$$

secondly, from the expression describing the spectrum of integral generation in time:

$$\Phi(\gamma)= I(\gamma, 0)\, I(\gamma, t) \int I_и(\tau)\exp[-cL_G\, \tau\, k(\gamma) / L_R]\, d\tau / \int I_P(\tau)d\tau, \quad (3)$$

where $I_P(\tau)$ is the shape of the laser pulse.

In most works on the application of the ICLA method, measured values of the spectral absorption coefficient of various lines of the gases under study or estimates of their limiting values are given. From an analytical point of view, this information is completely insufficient to determine the capabilities of intraresonator techniques, since such data are only intermediate in obtaining an analysis result, namely, information on the content of the determined component in the analyzed gas. To obtain such a result, additional information is needed on the absorption lines (their intensity S and width $\Delta\gamma_i$), as well as on the pressure of the analyzed mixture in the cuvette.

The partial pressure of the determined component can be found from the expression:

$$P_p = k(\gamma_i)(\pi\Delta\gamma_i / 2S) \quad (4)$$

The intensities of some absorption lines of molecules of various gases in the region of generation of neodymium (λ = 1.06 mkm) and ruby (λ= 0.69 mkm) lasers are given in Table. 1.

Table 1

Intensity S ($cm^{-2} \cdot Pa^{-1}$) absorption lines of molecules of some gases

λ, mkm	H_2O	CO_2	N_2	N_2O	NO_2	O_2	SO_2
1,06	10^{-14}	10^{-16}	$<3\cdot10^{-18}$	10^{-16}	$<3\cdot10^{-18}$	$<3\cdot10^{-18}$	$<3\cdot10^{-18}$
0,69	$1{,}2\cdot10^{-14}$	$<2\cdot10^{-18}$	$<2\cdot10^{-18}$	—	10^{-13}	10^{-17}	—

The absorption line width of inorganic gas molecules depends on both the gas pressure in the cell and the type of buffer gas and can vary from 0.05 to 0.2 cm $^{-1}$. The use of expression (4) makes it possible to obtain quantitative analytical information in spectrometers with a wide lasing band.

In a narrow-band version of the method, it was proposed [4] to use the following expression for the relationship between the absorption coefficient $k(\gamma_i)$ and the partial gas pressure P_p in the analyzed sample:

$$k(\gamma_i) = \chi_i P_p, \quad (5)$$

where χ is a coefficient that determines the absorption capacity of a unit of gas quantity; in the infrared range of the spectrum. For gases such as CH_4, CO_2, NH_3, NO $\chi_i \approx 10^2 - 10^3$ cm^{-1} MPa^{-1}.

At present, the most significant factor limiting the introduction of this method into analytical practice is, apparently, the complexity of processing the analytical signal when obtaining the determination result.

The simplest diagram of an intracavity laser spectrometer is shown in Fig. 2. Here, the analytical characteristics of the spectrometer are determined by both elements *I* and *II*, its fundamental capabilities depend, first of all, on the laser parameters: constancy, spectral distribution of the gain, width and smoothness of the lasing spectrum, duration of stable lasing in the vicinity of the investigated line, spectral lasing range, controllability values of duration and frequency of generation. The main condition for the fulfillment of the expression (Fig. 2) describing the generation intensity in the vicinity of the absorption line of the gas under study is the small width of the absorption line in comparison with the width of the laser. Under these conditions, a redistribution of the radiation intensity of modes occurs without changing the gain of the active medium, i.e. the laser simulates a multi-pass cell, and the intensity at the center of the absorption line decreases exponentially. In gas analysis, the width of absorption lines, as a rule, does not exceed 0.2 cm^{-1}; therefore, it is sufficient to provide a width of the lasing spectrum of at least 1 cm^{-1}.

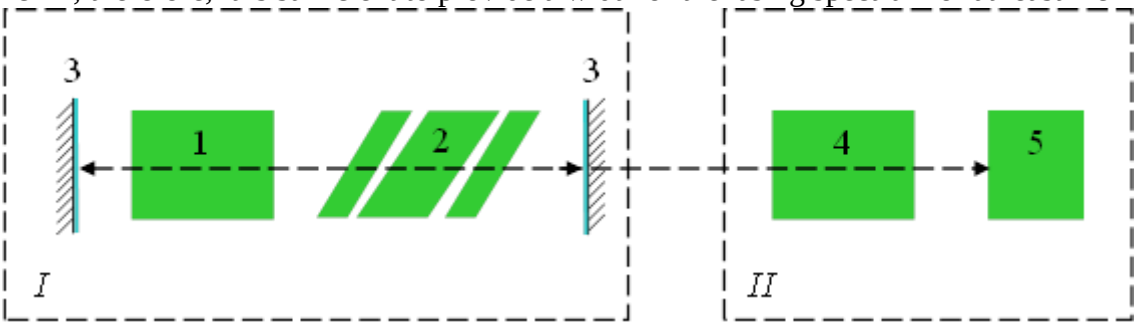

Figure 2 – Intracavity laser spectrometer diagram:

I - laser; *II* - radiation conversion and registration system. 1 - active element. 2 - absorption cuvette. 3 - resonator mirrors. 4 - spectrograph. 5 - radiation receiver.

The accuracy of recording the position and shape of the dip in the lasing spectrum largely depends on the nature of the spectral profile of the laser radiation. In this regard, special attention should be paid to the elimination of parasitic selection of the resonator Q-factor, which leads to the appearance of a line structure in the laser emission spectrum. The main reason for this is the return to the generation channel of a part of the radiation scattered or reflected by various elements of the laser system: the ends of the active rods, cell windows, surfaces of prisms, plates, resonator mirrors. The fight against this phenomenon can be carried out both by direct methods and by using various methods to reduce their influence.

Direct attenuation of reflection and scattering is carried out, first of all, by installing, if possible, all intracavity surfaces at the Brewster angle to the direction of the generated radiation, by thickening the used plane-parallel plates (cell windows, etc.), using wedge-shaped substrates for resonator mirrors, improving the quality of manufacturing and processing all parts of the laser system. A decrease in the influence of scattered and reflected radiation is achieved, first, by increasing the length of the laser cavity; second, by displacing the structure of the radiation spectrum during a lasing pulse [5-7].

Another important parameter is the continuous generation time. As indicated earlier, the development of a dip in the lasing spectrum occurs during the time of stable lasing in the vicinity of the absorption line of the gas under study. As a rule, this time is much shorter than the full generation time, and in the best case reaches 2-3 ms. As shown in [3], in order to determine the absorption coefficients at the level of 10^{-9}-10^{-10} cm^{-1}, it is necessary to achieve a continuous generation time no worse than 1-10 ms.

When choosing the type of laser for solving a particular analytical problem, the optimal conditions are when the laser generation region coincides with the strongest absorption lines of the gas under study. At present, the most widely used in spectrometers is ruby (λ = 694 nm); neodymium (λ= 1.06 microns); LC (λ ≈ 600 nm); helium-neon (λ= 3.39 microns) lasers.

The sensitivity of the method can be increased by changing the laser generation frequency, both in a pulse and from pulse to pulse [5]. One of the methods for expanding the dynamic range of the determined gas concentrations is changing the generation time and the filling factor of the laser cavity. Various variants of the schemes of resonators and elements of laser spectrometers can be found, for example, in [3,4].

To decompose laser radiation into a spectrum, a spectrograph is usually used or, if it is necessary to achieve good resolution (up to thousandths of a cm^{-1}), Fabry-Perot interferometers. The intensity distribution in the laser radiation spectrum is recorded using photographic or multichannel photoelectric detectors. The system for conversion and registration of laser radiation largely determines the sensitivity, spectral resolution, as well as the possibility of using instantaneous or integral methods for measuring and calculating absorption coefficients.

To achieve the maximum sensitivity of the spectrometer when choosing a particular spectral device, it is necessary to minimize the influence of instrumental distortions in the laser radiation spectrum. The influence of the instrumental function on the shape of the dip in the lasing spectrum of the laser can be neglected if the width of the absorption lines is 10-30 times greater than the width of the instrumental function of the spectral device.

The main requirements for photodetectors are, first, uniform spectral sensitivity in the operating region of the generation wavelengths; secondly, a large dynamic range in terms of the intensity of the recorded radiation; thirdly, good spatial resolution.

Conclusions.

Under the action of water vapor in the working cell, the radiation power of the ring laser decreases, which leads to the appearance of a difference signal from two germanium photosensors. To expand the dynamic range and improve the sensitivity of photosensors, filtering of the pump radiation is required, which can be done either with a light filter or with a specially designed fiber absorber. Both lasers and photosensors are placed in a passive thermostat to equalize their temperatures. Temperature equalization is necessary to prevent a temperature shift in the generation frequency of the fiber laser, which can lead to a change in the absorption coefficient of the fiber. Thus, the developed sensor for monitoring water vapor with a differential signal registration scheme has the following parameters: operating wavelength of a ring laser on an erbium fiber λ=1.55 μm; wavelength and pump power, respectively, λ=980 nm and P_{pump} =100 mW; sensitivity to water vapor at the level of 10^{-5} - 10^{-6} %.

Bibliography

1. Pakhomycheva L.A. et al. Letters JETF. 1970, vol. 12. no. 2. pp.60-63.
2. Peterson N.C. et al. J. Opt.Soc.Am. 1971, V.61.6. pp. 746-750.
3. Lukyanenko S.F., Makagon M.M., Sinitsa L.N. Intracavity laser spectroscopy: Fundamentals of the Method and Application. Novosibirsk, SO Science, 1985, 120p.
4. Lebedev A.V., Popov A.I. JPS. 1986, Vol. 44. no 2. pp. 219-225.
5. Lukyanenko S.F. JPS. 1985, T.43. no 2. pp. 184-188.
6. Laser spectroscopy of atmospheric gases: Under. ed. V.P. Lopasov. Tomsk, Ed. IOA AN, 1978, 200p.
7. Khasanov M.M., Ochilov B.H., Gulyamova S.T., Ibragimova B.B., Aripova M.X. Method of Ion-plasma Doping of Optical Fiber. International Journal of Advanced Research in Science, Engineering and Technology. Vol. 7, Issue 11, November 2020, pp. 15889-15896.

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