

LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS https://doi.org/10.1070/QEL16438

Laser two-channel gas analyser

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Abstract. **The technical scheme of a remote laser analyser of vapours of hazardous and toxic substances based on two IR sources (a tunable $^{13}C^{16}O_2$ isotope laser and a quantum cascade laser) is described. The developed optical scheme of the analyser, which is identical for both sources, makes it possible to fabricate a rather compact device. The use of two channels considerably extends the application field of the gas analyser. The possibility of using the gas analyser in stationary and mobile variants is provided.**

Keywords: *remote probing, laser gas analyser, IR spectroscopy, absorption spectroscopy.*

1. Introduction

Rapid and precise remote detection of traces of hazardous and toxic substances (HTS's) is very important to ensure safety in the case of natural and technological disasters, agricultural waste utilisation and terrorist attacks, as well as in ecology and medicine. To date, there exist a number of various methods and tools for detecting such substances, but there is no methods detecting these materials with a 100% probability. Therefore, it is necessary to develop new methods and technical tools that can increase the HTS detection efficiency.

The most promising methods for solving the problem of remote detection and identification of various HTS's are methods using laser probes. Most of numerous existing remote laser methods are described in recently published reviews [1, 2]. Of considerable practical interest for detection and identification of HTS's are methods of IR lasers spectroscopy. The mid-IR vibrational–rotational absorption spectra of molecules of some HTS's (for example, explosives) are highly specific and are determined by the symmetry and chemical composition of these molecules [3]. The IR light is invisible to naked eye, which allows one to perform remote detection unnoticeable for observers. To implement this method, one needs high-power tunable IR lasers. Promising sources for HTS detection systems using laser spectroscopy in the visible and near-IR ranges are solid-state lasers based on doped crystals, excimer lasers, diode lasers, He–Ne lasers and dye lasers, while metal vapour lasers, He–Ne lasers and CO and CO_2 lasers are used for detection in the mid-IR range [4, 5]. The appearance of high-power parametric and quantum-cascade lasers (QCLs) also makes it possible to develop new methods for detecting HTS traces [6].

A number of remote laser gas analysers that can detect HTS's using IR laser spectroscopy has been developed in recent years [7–9]. The aim of the present work was to design a compact optical remote laser gas analyser for detecting a variety of HTS's. The analyser will be able to provide a greater selectivity due to the extension of the range of the generation wavelengths and their tuning region, as well as due to an increase in the number of detection channels of the absorption at the track with a variable distance of 50–100 m.

2. Gas analyser scheme

The gas analyser consists of a laser radiation unit, a receiver unit and a data processing and control unit. The laser radiation unit of the gas analyser contains two probe lasers, namely, a $^{13}C^{16}O_2$ isotope laser tunable within the range of 10.99–11.4 μm and a QCL tunable within 7.1–7.6 μm with powers of 0.5 and 0.2 W, respectively. The gas laser spectrum includes intense absorption lines of such substances as acetone, methanol, benzene, nitrobenzene, chlorine, toluene and some others [10, 11]. The tuning range of the diode laser contains the absorption bands of acetone, sulphur dioxide, methanol and propane, as well as of vapours of surrogate and industrial explosive materials [11, 12].

To direct the radiation into the probe channel, we use one tunable collimator consisting of concave and convex spherical mirrors; the radiation of the used lasers is focused on a diffusely reflecting target. The radiation reflected from the target is collected by a mirror objective and forms an analytic signal. The signal is recorded by a receiver unit connected to a data processing and control unit.

To ensure precise focusing of the gas analyser on the diffusely reflecting target, the laser unit is additionally equipped with a visible diode laser (wavelength 0.532 μm).

Figure 1 presents the schematic of the gas analyser, which contains laser unit (*1*) consisting of three lasers (two probe lasers and a guiding laser), mirror collimator (*2*), a receiver unit consisting of receiving objective (*3*) and photodetector (*4*), a data processing and control unit including ADC card (*5*) and computer (*6*), and a supporting structure, i.e. optical breadboard (*7*).

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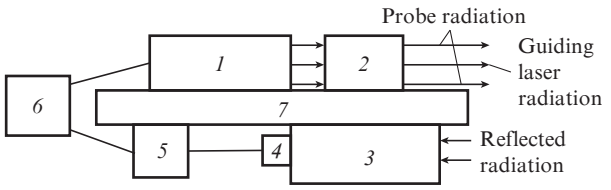

Figure 1. Scheme of the two-channel gas analyser: (*1*) laser unit; (*2*) collimator; (*3*) receiving objective; (*4*) photodetector module; (*5*) ADC card; (*6*) mirror objective; (*7*) optical breadboard.

Figure 2 shows the optical scheme of the gas analyser, which contains a laser unit consisting of three radiation sources (*1*, *2*, *3*) and mirror collimator (*4*); diffusely reflecting target (*5*); and a receiver unit, i.e., Cassegrain mirror objective (*6*) with a photodetector module consisting of compensating edge (*7*), a plate beam-splitter and two photodetectors (*8*) cooled with nitrogen using closed-cycle microcryogenic systems based on Stirling-cycle machines. Each photodetector of the module has the maximum sensitivity at the wavelength corresponding to the fundamental wavelength of one of the probe lasers. The beams of these lasers propagate symmetrically with respect to the optical axis of the mirror collimator. In addition, the axes of the IR radiation of the probe lasers are equally spaced form the axis of the visible beam of the guiding laser.

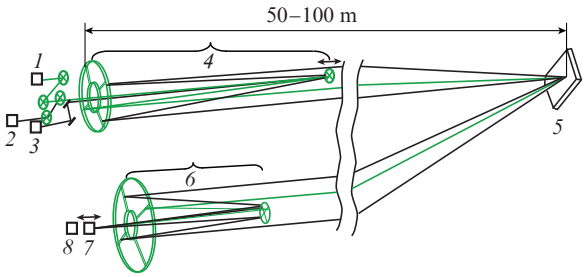

Figure 2. Optical scheme of the gas analyser: (*1*, *2*, *3*) lasers; (*4*) mirror collimator; (*5*) diffusely reflecting target; (*6*) mirror objective; (*7*) compensation wedge; (*8*) photodetector.

Focusing of the laser radiation on the diffusely reflecting target (distance 50–100 m) was automatically corrected by moving the secondary mirror component of the collimator along the optical axis. To move this component, we used a linear translator with a step motor. This range of probing distances was chosen because the maximum length of the available controlled path was 100 m and because a decrease in the minimum distance would cause vignetting of radiation on the main mirror of the objective and, as a result, made it necessary to increase its size and the size of the sensitive areas of the photodetectors.

Mirror objective (*6*) in the receiving unit was focused to a distance of 75 m. The optical axes of mirror collimator (*4*) and objective (*6*) intersected at a distance of 75 m as well. Because of this, the images of received echo-signals in the case of distances differing from 75 m shift, which causes vignetting of radiation on the photodetectors. To eliminate vignetting, we placed a germanium compensation wedge behind the receiving objective. The wedge was automatically moved by a linear $X-Y$ translator with step motors. The introduction of the movable compensation wedge into the optical scheme allows the received signal projections remain within the sensitive areas (1×1 mm) of each of the photodetectors at different distances to the diffusely reflecting target. The photodetectors themselves were spaced from each other and stationary fixed in the receiving module (Fig. 3). The laser beams were separated by a plate beam-splitter. The plate was coated with an antireflection layer for the wavelengths of one of the probe lasers.

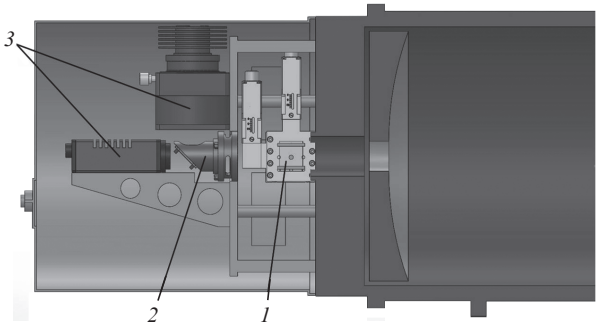

Figure 3. Photodetector mounted on the rear flange of the receiving objective: (*1*) compensation wedge on a linear $X-Y$ translator; (*2*) beam-splitter unit; (*3*) photodetectors.

If it is necessary to separate the radiation of one of the probe laser from the radiation of the other laser, the radiation of each of the probe lasers can be modulated. This situation may occur, for example, in the case of a manifold excess of the CO_2 laser power over the QCL power. In this case, despite the more favourable conditions for the QCL radiation propagation in the corresponding channel, the power of the scattered radiation of the CO_2 laser on the photodetector of this channel may be comparable with the QCL power and even exceed it.

For automatic correction of focusing of the collimator in the laser unit and of the objective in the receiving unit, the distance to the diffusely reflecting target was calculated on a computer. The calculation was performed by the delay time of the instant of the CO_2 laser pulse recording by the photodetector with respect to the instant of the pulse generation.

The data processing and control unit is responsible for the data transfer, processing and storage; for the control of the step motors of the linear translators used to correct focusing of the collimator and objective; and for the control of probe lasers (change of the pulse repetition rate and power and tuning of the probe wavelength).

3. Principle of the gas analyser operation

The gas analyser operates as follows. The probe laser radiation is focused by the mirror collimator on the diffusely reflecting target, reflected backward from it, collected by the objective and recorded by the photodetectors. The frequency spectrum of the echo signals is formed by tuning the frequency of the probe lasers. When a HTS (or a HTS marker) cloud appears in the probing channel, the spectrum of echo signals will contain holes caused by the absorption of laser radiation at wavelengths characteristic for each substance. Processing of echo signals yields the spectrum of selective absorption of the probe radiation by molecules of a HTS (or a HTS marker).

Computer-aided comparison of the spectra of echo signals in a 'pure' probing channel and in the presence of HTS (or HTS marker) molecules allows the gas analyser operate in an automatic regime.

The minimum time of continuous scanning over the entire spectral range is 30 s. Scanning can be performed by the gas laser lines. It results in an increase in the analyser sensitivity, while the scanning time grows.

The gas analyser power supply voltage is 24 V, and the consumed power is 1 kW. The gas analyser was $1000 \times 1000 \times 700$ mm in size and weighed 100 kg. These characteristics allow one to use the analyser, in particular, in a portable version mounted on a mobile carrier and supplied from an onboard grid.

4. Control experiment

The operational capability of the gas analyser was tested with the use of ammonia (NH_3). This gas was chosen due to the following reasons: its absorption band lies within the wavelength range of the probe lasers; it is hazardous itself, is used in production of, for example, some surrogate explosive substances, and is a marker of these explosives in the case of their degradation.

The experiment was performed according to a previously developed scheme [13], in which a beam from the laser unit of the gas analyser propagates through an absorption cell positioned in the probing channel and containing vapours of a tested material, falls on a diffusely scattering target, and is scattered from it. The scattered radiation, which contains information about absorption in the channel, partially returns to the receiving unit of the gas analyser. The absorption cell was a metal tube 68 mm in diameter and 620 mm long. The tube edges were closed by ZnSe windows, while the cell walls were equipped with pump adapters. The control experiment was performed with a specially prepared ammonia–air mixture with ~200 ppm of ammonia. The cell was filled with this mixture at a total pressure of 1 atm. As a target, we used a sandblasted brushed duralumin leaf. The target and the cell were spaced from the gas analyser by 75 and 65 m, respectively.

Figure 4 shows the experimentally recorded echo-signal spectrum, which contains a typical hole caused by the absorption of laser radiation by the ammonia vapour. Scanning was performed by the laser generation lines with a delay of 1 s. The pulse repetition rate was 100 Hz. The scanning time was 45 ns. The maximum sensitivity with respect to ammonia under our experimental conditions was ~40 ppm.

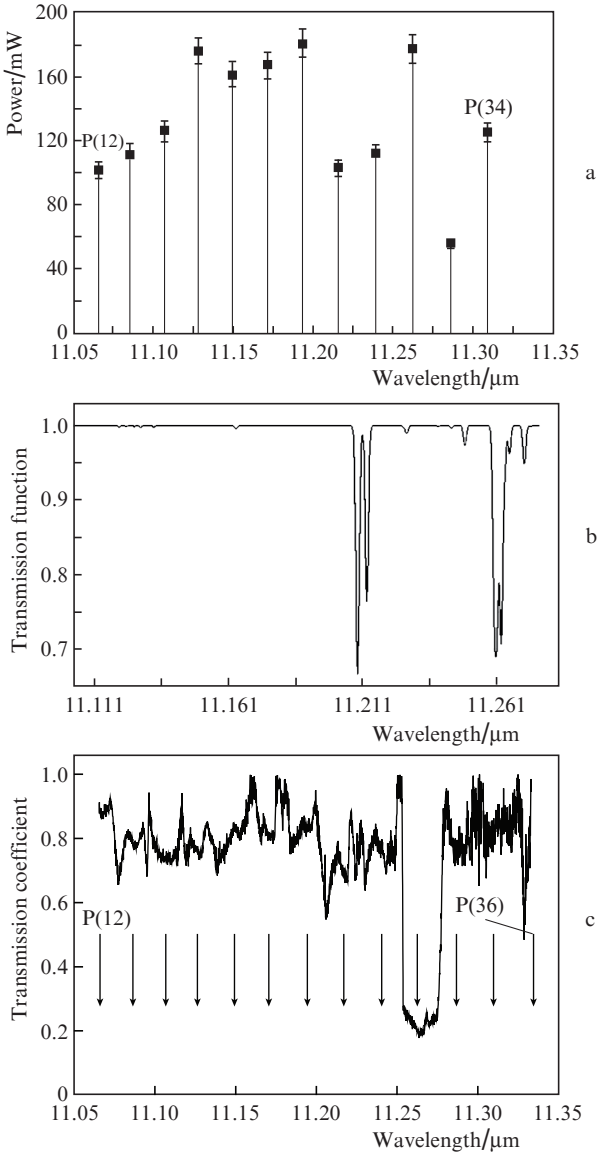

Figure 4. (a) Power distribution over the $^{13}C^{16}O_2$ laser lines, (b) ammonia transmission function calculated using the Spectra information system [14] for our experimental conditions, and (c) dependence of the echo signal [i.e., of the transmission coefficient of a cell 620 mm long with a mixture of ammonia (~200 ppm) with air at a pressure of 1 atm and a temperature of 18 °C] on the $^{13}C^{16}O_2$ laser wavelength measured at a distance of 65 m. The arrows in Fig. 4c show the wavelengths of the used laser lines.

5. Conclusions

The advantages of the proposed gas analyser consist in the fact that the developed optical scheme, which is the same for three sources, allows one to design a rather compact device. The use of two tunable IR lasers makes it possible to detect the presence of vapours of various substances in the atmosphere, including HTS's whose absorption spectra lie in the mid-IR range. The wavelength tuning of the lasers increases the gas analyser selectivity due to recording the spectral features of HTS (or HTS marker) molecules that distinguish them from other molecules with similar optical properties. This decreases the number of false signals of the device.

The use of mirror optics in the transmitting and receiving systems of the gas analyser makes it possible to use different light sources and photodetectors, which facilitates the development of combined systems based on the use of various laser technologies for detection of HTS's. Apparently, it is these systems that will play a key role in the future.

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