Full Paper

Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201800171

Detection and Identification of the Traces of Explosives with Using of Active Spectral Imaging

Liudmila V. Kuzovnikova,*[a] Eugene V. Maksimenko,[a] Alexander B. Vorozhtsov,[a, b] Anatolii A. Pavlenko,[a] Alexander V. Didenko,[a] and Sergei S. Titov[a]

Abstract: An optical-electronic laser complex for the stand-off detection of traces of explosives was developed with using of the Active Spectral Imaging. The tuning and automatization of the developed complex were performed. Experimental researches in detection of traces of various types of explosives on different substrates were carried out. On average, the probability of detection was 89 % and the probability of identification was 91 %.

Keywords: explosives · detection · hyperspectral imaging · automatization

1 Introduction

Every year it becomes more and more urgent the fight against terrorism because of expansion of geography of terrorism and upgrading of material and technical equipment of terrorist organizations. In response, worldwide new methods and means of detection of explosives are developed [1–4]. The main requirements of modern detection systems are high detection speed, high sensitivity and selectivity, as well as the safety of inspectors [5–9].

It is generally recognized that any single method of detection of explosives can't provide an absolute guarantee of detection and only a combination of several methods of control provides a guarantee of safety. For example, in a joint project (NATO-Russia) named as «Stand-off detection explosives» (STANDEX) in 2013 in the Paris metro in real-time condition with a large crowd of people, the experimental stand developed on a base of few methods was successfully tested. The safety of personnel in the first place can be provided by standoff methods for detection and identification. Recently the method of standoff research of objects based on optical spectral analysis and on recognition of images which is named like "Active Spectral Imaging (Active SI)" method rapidly develops [10–12].

"Active SI" method consists in irradiating by tunable source of laser radiation of the surface of an object with trace amounts of explosive.

The interaction of laser radiation with the substance being studied is detected as a form of inverse diffusely scattered radiation by a radiation receiver with a multi-element array. As a result of successive registration of the response at each wavelength, a multidimensional spatial-spectral image, called the "hypercube" of the data, is obtained.

Each frame (image) of the hypercube corresponds to reflection from the studied surface at a certain wavelength, and each pixel of the hypercube contains a reflection spectrum at a specific location of the studied surface.

Identification results are presented as a detection map where each pixel has an estimate based on the similarity of the registered spectral curves of the studied object with the reference spectrum. It allows to distinguish and to identify different materials.

"Active SI" method has a high sensitivity and spatial resolution, allows to provide non-contact detection and identification of explosives. In addition, it is one of the few methods capable to achieve the high-speed scanning of surfaces while remaining safety for humans.

This paper presents the development and automation of optic-electronic laser system for standoff detection of explosive traces in the IR region based on the method "Active SI".

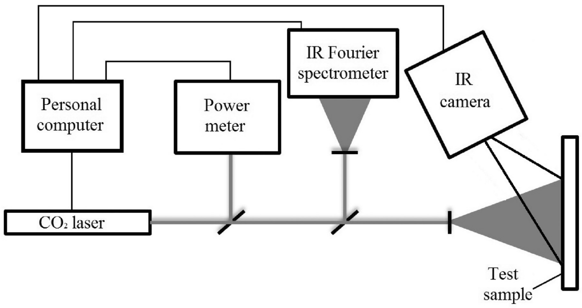
2 Experimental Section

2.1 Development of Optical-Electronic Complex

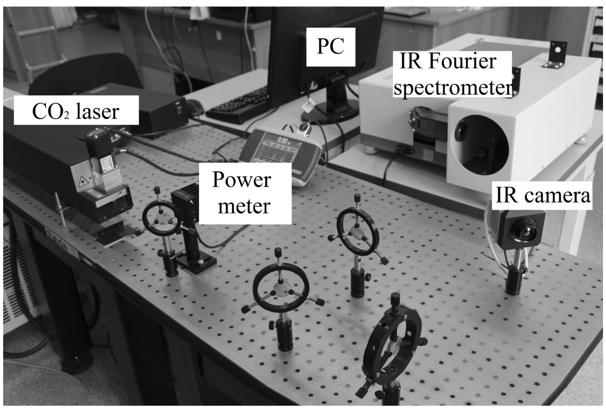
A team of authors proposed and developed an optical-electronic complex based on the method "Active SI", the scheme and the appearance of which are shown in Figure 1 [13].

The study is performed with using of instrumental base of the Biysk regional centre of common usage of the SB RAS (IPCET SB RAS, Biysk).

[a] *L. V. Kuzovnikova, E. V. Maksimenko, A. B. Vorozhtsov, A. A. Pavlenko, A. V. Didenko, S. S. Titov*
Institute for Problems of Chemical and Energetic Technologies SB RAS, 659322, 1, Sotsialisticheskaya Str., 659322, Biysk, Altai Krai, Russia
**e-mail: lvchernyshova@bk.ru*
[b] *A. B. Vorozhtsov*
National Research Tomsk State University 634050, 36, Lenina Avenue, Tomsk, Russia



(a) Block diagram



(b) Appearance

Figure 1. Optical-electronic complex.

For the purpose of irradiating of the surface with particles of explosives, a CO_2 laser LCD-5WGT tunable in the range from 9.2 to 10.8 μm was used.

In the laser tuning range, there are 56 active wavelengths of radiation. An obligatory condition for the operation of the laser is a presence of forced water cooling of emitter and power source.

Cooling and autonomous operation from the water supply source are provided by the circulation cooler LAUDA WK 2200. The laser radiation power is controlled by a special-form signal generator GCC-40, which generates an external controlling signal with the following characteristics:

- the pulses are TTL level (positive);
- frequency of 2–4 kHz;
- filling the period from tens of microseconds to continuous (maximum) mode.

The average laser radiation power is proportional to the area of filling of the control signal.

The optical system of the complex includes two beam splitting plates made of ZnSe, which separate the incident laser radiation in order to determine its parameters (radiation power and wavelength), and a negative meniscus lense made of ZnSe ($f = 50$ mm) for increasing of the detection area.

The power meter UP19K-30H-H5-D0 (Gentec-EO) was chosen for recording of power of probing radiation at overall spectral range. Operation and registration of information are implemented with using of the Maestro monitor.

Standoff detection of spectrum with the further automated determination of wavelength of radiation is implemented by IR Fourier spectrometer "Infralum FT-801" and an associated foster mirror telescope.

For registration of received optical signals (image hypercube), a compact uncooled microbolometric Gobi-384 camera operating in the range of laser wavelength tuning was selected. The difference between the coefficients of registered reflection (absorption) of surface materials and traces of explosives over the entire range of tuning of the radiation source (IR spectra) determines the possibility of identifying of studying substance on the surface.

2.2 Tuning and Automation of Measuring Complex

In order to reduce the detection time and also for continuous monitoring of parameters of the tunable CO_2 laser during the measurement process, an automated measuring system is developed. The scheme of it is shown in Figure 2.

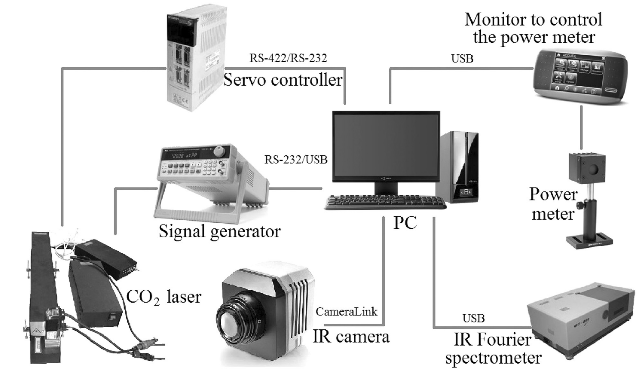


Figure 2. Scheme of the automated measuring system.

Automatization of the laser complex control was carried out by means of PC. The software of complex is developed in Python programming language.

The software consists of several modules.

1) The module of determining of characteristics of laser radiation. It is made for obtaining of calibration data of parameters of laser radiation, and also for continuous or periodic monitoring of laser radiation characteristics during hyperspectral data recording process [14].

As the result of a calibration the module automatically generates a calibration file with the parameters of laser radiation for each of the 56 wavelengths (the duty cycle of the controlling signal, the radiation power, wavelength of emission lines).

2) Module of automatic registration of spectral images of the illuminated surface. As a result of the module implementation, the two hypercubes of "active" (background + laser) and "passive" (background) frames are formed. Registration of background set of images is necessary for further allocation of area of laser action.
3) The module of processing and interpretation of hyperspectral data with the presenting of conclusion about the presence of traces of explosives on the studying surface [15].

The pre-processing of obtained hyperspectral data and their analysis are implemented in this module.

At the stage of pre-processing, the area of laser exposure is determined from the difference images of "active" (with laser illumination) and "passive" (without laser illumination) frames with further allocation of laser spot at all wavelengths. The allocation of the intersection of the area of action is carried out by comparing with the threshold value as the value of the own noise of camera. At the experimental studies it was found out the maximum value of the standard deviation of the values of thermal noises of the matrix, which was 150 relative units of brightness.

Also at the stage of pre-processing, speckle noise is suppressed programmatically. Suppression is performed by median filtering with a smoothing area of 8×8 pixels. At carrying out of experimental studies and calculating the spectral density of the noise power by Fourier transform, a reduction of the high-frequency component of the noise power in 40 times is ensured.

The immediate analysis includes two methods of identification of substances: method of Spectral Angle Mapper (SAM) and the Minimum Distance (MD) method [16]. Analysis of the hyperspectral cube by these methods, unlike other methods of identification, can be carried out practically in real time.

When the obtained spectra were compared with the reference one taken from the library, a threshold value was experimentally chosen. Under that the substance is identified as explosive. If the received spectrum differs from the reference spectrum less than 20 %, the image pixel is accepted as an explosive. In case the obtained spectrum corresponds to several reference spectra of explosives, the studied substance is detected, but not identified (i.e., the type of the explosive is not determined).

In addition, a graphic indication of the fact of detection of traces of explosives on the studying surface was implemented. It displays the location, shape and number of pixels occupied by the trace in the registered image, a color indication of the type of explosive gotten from the software database (white – HMX, red – RDX, green – TNT, blue – PETN, purple – the type of explosive is unknown). Additionally, the detected types of explosives are displayed in legend.

Each of the described modules can be executed separately from the others, as independent program and as a part of a single software package.

As a result of debugging and testing of the software, the whole process of detection and identification of traces of explosives was automated.

2.3 Preparation of Samples

For testing the performance and studying of the detecting characteristics of the complex, four test samples (a substrate with applied sample of explosive of a certain concentration) were prepared. As the explosives HMX, RDX, TNT and PETN were selected.

Samples were prepared by micropipetting with using of the mechanical dispensers Proline Plus (Sartorius) and by weighing on the analytical balance CAS CAUX 220 with a fission rate of 0.0001 g.

At studying of the trace concentrations of explosives, it is necessary to take into account the additional component of the radiation reflected from the substrate materials in the spectral measurement area.

By the nature of the influence of the substrate material on the probing radiation in the recorded area, the investigated surfaces can be divided into two groups, into which the analyzed samples were divided.

The first group are the mirror-reflecting surfaces (polished metals, glass). The intensity of the reflected signal from the substrate for materials of this group will be several orders higher than the intensity of the trace signal (depending on the thickness of the investigated layer of matter). In the studying of the substrates of this group, it is necessary to install the IR camera in special way to prevent the passing of reflected laser radiation into it. In this case, the possibility of damage to the photodetector matrix is excluded. In addition, only the trace signal enters the camera. Samples of the first group were made on a glass substrate. The appearance of the samples is shown in Figure 3.

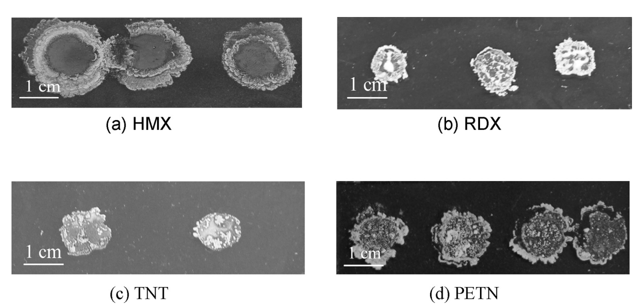
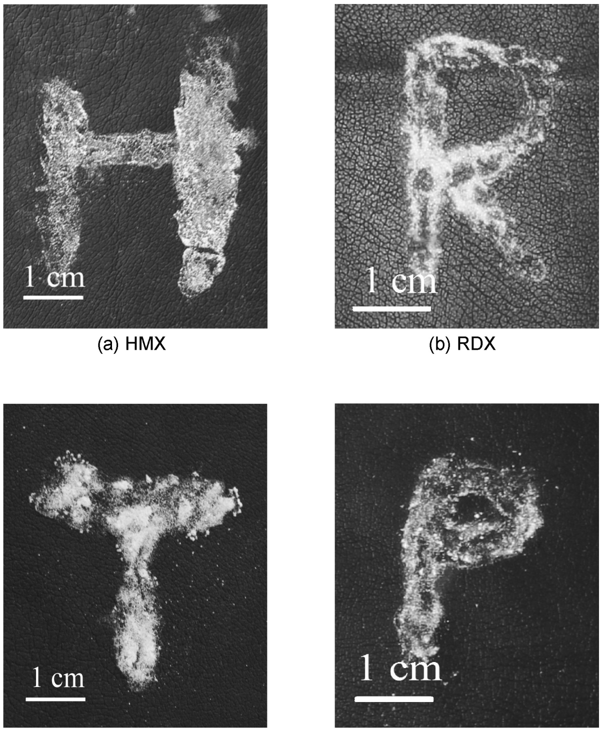


Figure 3. The first group of test samples on glass.

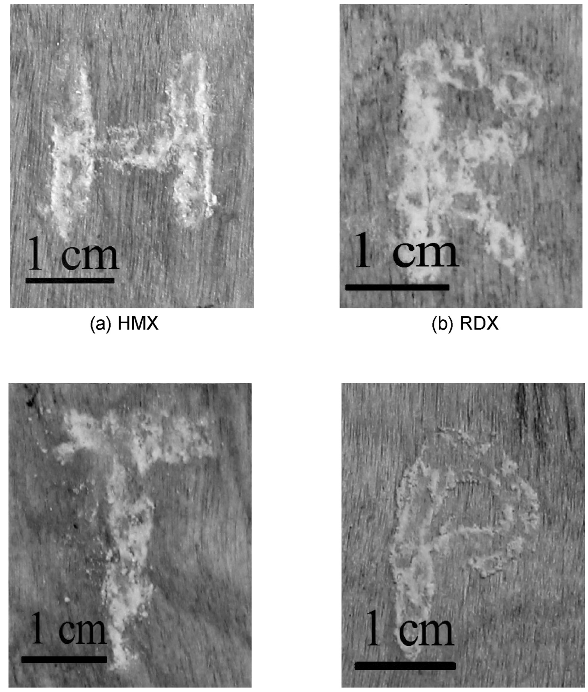
The number and shape of traces on the substrate varied depending on the type of explosives. The average surface concentration of substances was 0.97 $mg\,cm^{-2}$.

The second group includes diffusely reflecting surfaces, for example, cloth, paper, leather, wood. Identification of traces of the required explosives on such surfaces is more difficult than for the materials of the first group, because of an additional interference from diffusely reflected radiation of the substrate. As a substrate, artificial leather and plywood are chosen from this group. Appearances of test samples of the second group are shown in Figure 4 and 5.



(a) HMX (b) RDX (c) TNT (d) PETN

Figure 4. The second group of test samples on an artificial leather substrate.



(a) HMX (b) RDX (c) TNT (d) PETN

Figure 5. The third group of test samples on a plywood substrate.

Samples are made in the form of letters: HMX – «H», RDX – «R», TNT – «T», PETN – «P». The average surface concentration of the samples on artificial leather was 2.7 mg cm$^{-2.}$

The average surface concentration of samples on plywood was 2.6 mg cm^{-2}.

As the control samples needing for detection of false positive results the clean substrates of the same materials as the traces with explosive traces were used.

2.4 Testing

Before carrying out the experimental studies, it was necessary to evaluate the safety of the laser radiation on the surface of the studied object, and also the skin and eyes of a human.

At a uniform distribution of the radiation intensity over the entire beam section with the help of a scattering optical element, the power density of the laser radiation (I) on the target is equal to:

$$I = \frac{P_{laser} \cdot k_1 \cdot k_2}{\pi \cdot l^2 \cdot tg^2\left(\frac{\alpha}{2}\right)},$$

where P_{laser} is the output power of the laser radiation, k_1, k_2 are the transmission coefficients of the beam splitters, l is the distance from the scattering optical element to the target, and α is the scattering angle after the scattering optical element.

The output power of laser radiation is 1.6 ± 0.1 W. The laser beam of the tunable IR laser of the LCD-5WGT is separated by each of the two beam splitters in a ratio of 0.3:0.7 (reflection: transmission). After that, the radiation is scattered by an optical element with an opening angle (α) equal to 30° and the object with traces of the test substance on the surface is highlighted. When detecting at a distance of 0.5 m, the power density of the laser radiation on the target is 1.37 ± 0.09 mW cm^{-2}. The maximum permissible exposure for continuous IR radiation is 1000 mW cm^{-2} [17]. Consequently, such of experimental studies are safe for the human eyes and skin.

For the obtaining of statistical data, a complete study cycle with each sample was carried out 20 times.

In addition, for estimation of the spatial resolution of the complex, a number of experiments were carried out with changing the position of the sample relative to the studying scene.

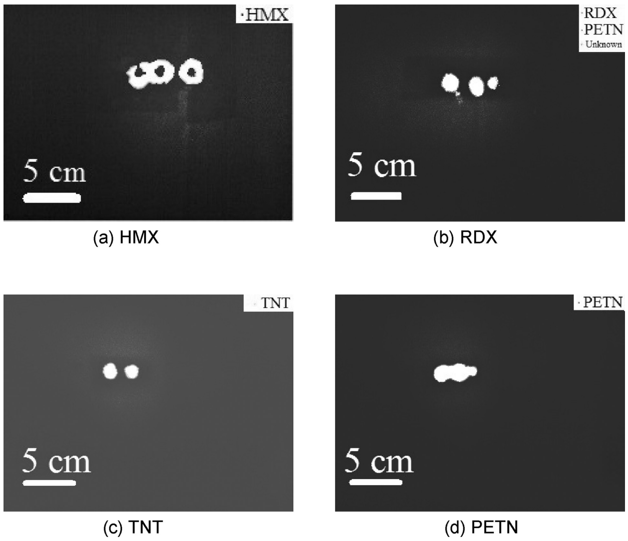


Figure 6. The result of the analysis of test samples of the first group obtained by the SAM.

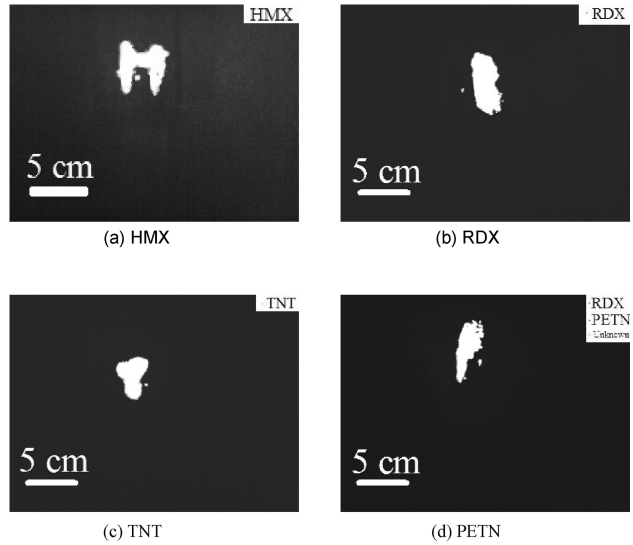


Figure 7. The result of the analysis of test samples of the second group by the SAM.

The results of identification of the first group of samples by the SAM are presented in Figure 6.

In this series of experiments, the traces of the samples of the HMX, TNT and PETN, entering the region of the action of laser radiation, were found and correctly identified. The RDX sample was localized, but in some individual cases it was not possible to determine the type of the explosive. In the study of the control sample in all experiments the false positive result wasn't found.

Experiments on detection of real samples of explosives were carried out with different settings of amplification of the radiation receiver. It didn't affect the results of detection due to the normalization of spectral images at the stage of pre-processing of the hypercube.

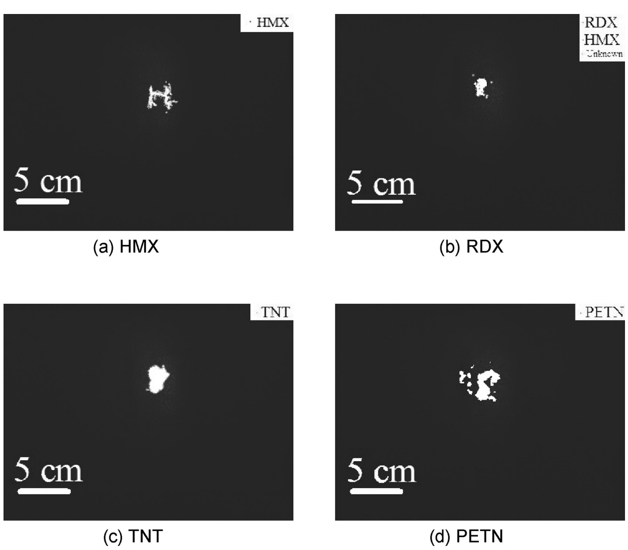


Figure 8. The result of analysis of test samples of the third group by the SAM.

The results of processing the registered samples on the substrate of artificial leather by SAM are shown in Figure 7.

As it can be seen from the obtained data, the PETN sample was localized, but the identification of the type of explosive caused the difficulties. The remaining samples were localized and correctly identified. As in experiments with the first group of samples, the results of the control sample processing did not give false positive responses.

The third series of experiments was carried out with samples on a plywood substrate. The results of processing of the registered samples by the SAM are presented in Figure 8.

In the sample of RDX the type of explosive wasn't identified. The rest samples were localized and correctly identified, but the images shown the presence of pixels with false positives. In the experiments with the control sample it was found out a 10 % probability of false positives.

The difference in the number of detected pixels by the SAM and the MD did not exceed 10 %.

3 Results and Discussion

Based on the results of the carried out experiments, the detection probability and the probability of identification of the explosive type at establishing the fact of detection for each sample (substrate - explosive) were determined. Probability of detection is shown in Table 1.

It can be seen from the table that the developed measuring complex has the highest probability of detection on a glass substrate, while the most detectable explosive was an

Table 1. Probability of detection of explosives with using of the developed measuring complex.

Substrate	HMX, %	RDX, %	TNT, %	PETN, %	$P_{D.avg}$, %
Glass	95	90	95	95	94
Artificial leather	90	85	90	85	87
Plywood	90	85	85	80	85
$P_{D.avg,}$ %	92	87	90	87	89

HMX. On average, the probability of detecting of explosives was 89%.

The probability of identifying of the type of explosive at establishing the fact of detection with using of the developed measuring complex is presented in Table 2.

Table 2. The probability of identifying the type of explosives at establishing the fact of detection with using of the developed measuring complex.

Substrate	HMX, %	RDX, %	TNT, %	PETN, %	$P_{I.avg}$, %
Glass	100	89	100	95	96
Artificial leather	100	88	100	82	92
Plywood	94	82	88	81	86
$P_{I.avg,}$ %	98	86	96	86	91

The best identified was an HMX. On average, the probability of identification in establishing the detection fact was 91%.

The theoretically calculated limit of detection of an HMX by the method described in [18] for a given composition of the measurement complex is 0.2 $mg\,cm^{-2}$. This limit can be reduced if the microbolometer camera will be replaced with another model with better signal-noise ratio. For example, for cooled cameras with an equivalent noise temperature difference of 5 mK, the detection limit is 20 $ng\,cm^{-2}$.

4 Conclusions

An optical-electronic laser complex for standoff detection of explosive traces by "Active SI" method based on a tunable CO_2 laser was developed. The setting up and automatization of the developed complex were performed, the control software was developed, as a result of which a calibration file with the characteristics of laser radiation is formed, a set of spectral images is recorded and processed, and information on the presence of explosives is reported. A number of experimental studies on the detection and identification of explosive traces were carried out. On average, the probability of detecting explosives was 89%. The best results were demonstrated on mirror-reflecting surfaces (glass). In this case, the probability of detection was 93%. At establishing the fact of detection, the HMX was identified best of all. On average, the probability of identification in the case of detection was 91%. The best identification results are also achieved on the glass. The probability of identification was 96%. Further research will be devoted to increasing of the nomenclature of the substances, as well as to perfectioning of the laser complex to improve its basic performance characteristics (probability of detection, detection limit, detection distance, etc.).

References

[1] L. A. Skvortsov, *Laser methods for remote detection of chemical compounds on solid surfaces*, Technosphera, Moscow, **2014**, p. 208.

[2] P. M, Pellegrino, E. L. Holthoff, M. E. Farrell, *Laser-Based Optical Detection of Explosives*, CRC Press Taylor&Francis Group, Boca Raton, **2015**, p. 405.

[3] S. Wallin, A. Petterson, H. Östmark, A. Hobro, Laser-based standoff detection of explosives: a critical review, *Anal. Bioanal. Chem.* **2009**, *395*, 259–274.

[4] M. Krausa, A. Reznev, *Vapour and Trace Detection of Explosives for Anti-Terrorism Purposes*, Springer Science + Business Media, Dordrecht, **2004**, p. 152.

[5] A. Petterson, I. Johansson, S. Wallin, M. Nordberg, H. Östmark, Near real time standoff detection of explosives in a realistic outdoor environment at 55 m distance, *Propellants Explos. Pyrotech.* **2009**, *34*, 297–306.

[6] A. Dogariu, A. Pidwerbetsky, Coherent anti-stokes Raman spectroscopy for detecting explosives in real time, *Chemical, Biological, Radiological, Nuclear, and Explosives Sensing XIII.* **2012**, *8358*, 1–9.

[7] G. Bunte, M. Heil, D. Röseling, J. Hürttlen, H. Pontius, H. Krause, Trace Detection of Explosives Vapours by Molecularly Imprinted Polymers for Security Measures, *Propellants Explos. Pyrotech.* **2009**, *34*, 245–251.

[8] F. Schnürer, M. Rieger, A. Eberhardt, J. Aniol, H. Krause, Localisation of IED manufacturing facilities by detection of explosives in sewage water, *10th Security Research Conference. Proceedings,* Berlin, Stuttgart: Fraunhofer Verlag. **2015**, 285–291.

[9] J. M. Nilles, T. R. Connell, S. T. Stokes, H. D. Durst, Explosives Detection Using Direct Analysis in Real Time (DART) Mass Spectrometry, *Propellants Explos. Pyrotech.* **2010**, *35*, 446–451.

[10] F. Fuchs, S. Hugger, J. Jarvis, Q. K. Yang, R. Osterdorf, Ch Schilling, W. Bronner, R. Driad, R. Aidam, J. Wagner, Imaging standoff trace detection of explosives using IR-laser based backscattering, *Micro- and Nanotachnology Sensors, Systems, and Application.* **2016**, *9836*, 1–9.

[11] B. E. Bernacki, T. A. Blake, A. Mendoza, T. J. Johnson, Visible hyperspectral imaging for standoff detection of explosives on surfaces, *Optics and Photonics for Counterterrorism and Crime Fighting.* **2014**, *7838*, 1–7.

[12] M. E. Morales-Rodriguez, L. R. Senesac, T. Thundat, M. K. Rafailov, P. G. Datskos, Standoff imaging of chemicals using IR spectroscopy, *Micro- and Nanotachnology Sensors, Systems, and Application.* **2013**, *8031*, 1–8.

[13] A. A. Pavlenko, E. V. Maksimenko, L. V. Chernyshova, Stand-off detection of HMX traces by active spectral imaging with a tunable CO_2 laser, *Quantum Electron.* **2014**, *44*, 383–386.

[14] A. A. Pavlenko, E. V. Maksimenko, L. V. Chernyshova, Automated System for Determining of Characteristics of Tunable

CO_2-laser, *Datchiki & Systemi (Sensors & Systems).* **2015**, *8*, 33–37.
[15] E. V. Maksimenko, L. V. Chernyshova, A. V. Didenko, Applying of Methods of Processing of Hyperspectral Data for Identification of Traces of Explosives, *17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices EDM 2016: Conference Proceedings*, Novosibirsk State Technical University, **2016**, 358–363.
[16] J. A. Richards, X. Jia, *Remote Sensing Digital Image Analysis*, Springer-Verlag Berlin Heidelberg, **2006**, p. 454.
[17] American National Standards Institute, American National Standard for Safe Use of Lasers, ANSI Z136.1-2007 (Laser Institute of America), **2007**.
[18] A. A. Pavlenko, E. V. Maksimenko, L. V. Chernyshova, A. V. Didenko, Determination of Threshold of Sensitivity of Setup for Stand-off Detection of Traces of Explosives, *Polzunovsky vestnik*. **2016**, *4*, 68–72.

Manuscript received: May 29, 2018
Revised manuscript received: September 11, 2018
Accepted: September 11, 2018
Version of record online: November 25, 2018

