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OPTOELECTRONICS

Lasers in the dual use technologies

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Abstract. In the more developed countries the use of modern technologies in the national economy is a general process allowing joint funding of a security research and development by both sources, state and private. The last one is especially involved in applications of modern technologies. One of the examples of important modern technologies being under development in many countries are dual-use technologies, which include IT technologies, sensors, effective energy sources, material science, nanotechnology, micro- and nano-electronics, photonics, biotechnology and quantum medicine.

In this paper chosen technologies fulfilling the needs of the military technique and security monitoring systems, which have found their applications in the different branches of industry like power engineering, transportation, construction industry, metrology, protection of environment and the medicine, are discussed. The examples include the devices and lasers systems for different threats monitoring, which have been developed at the Military University of Technology. The research studies carried out on the analysis of various materials based on their spectroscopic characteristics: absorption, emission, dispersion, polarization and fluorescence in different mediums have led to the development of laser telemetry devices, environment monitoring devices and spatial imagery, as well as devices for medical diagnostics and therapy. Mentioned systems are composed of functional modules, which were developed to meet the real needs. These systems can be expanded further by addition of extra detectors of chemical materials and physical properties, and improving measuring functions and data transmission and processing.

Key words: lasers, sensors, multispectral imaging, environment monitoring, Dual Use Technology.

1. Military applications of lasers

The equipment utilizing optical sensors systems including laser devices, detection and thermovision systems, is an important component of modern armament and military equipment. Integrated electro-optical systems are involved in almost all types of troops and military services and the areas of operation: from tactics through strategy; from single soldier training through a number of anti-tank, anti-aircraft anti-missile weapon systems [1]. Table 1 contains the list of basic applications of laser devices in military technology. As it is shown in Table 1, laser devices are primarily used as the emitters of radiation. Most of optoelectronic systems consist of a close-coupled transmitter-receiver system. Modern optoelectronic military systems are used in the spectral range from the ultraviolet to far infrared. For instance, some homing missiles use the ultraviolet spectrum range as a supplementary band and missile start detection systems. The observation and targeting systems as well as some laser transmitters of range-finders and navigation systems work in the visible spectrum. The essential role in the military applications plays the infrared (IR) spectral range. The atmosphere of Earth strongly affects the transmission of optical radiation, hence the useful spectral ranges, including IR, are located in the atmospheric transmission windows. These atmospheric transmission windows are in the long-wavelength infrared (LWIR – 8–14 μm), which provides an excellent visibility of most terrestrial objects including low-temperature objects, mid-wavelength infrared (MWIR – 3–5 μm) mainly utilized for higher temperature objects, the short-wavelength infrared (SWIR – 1.5–1.8 μm and 2.0–2.4 μm) and near infrared (NIR – 0.7–1.1 μm).

The studies, carried out for many years at the Military University of Technology, in the area of lasers: theory and technology; diagnostic laser measurements; modulation methods and impact of lase radiation on matter, have allowed to implement many developments including laser range finders, shooting simulators and fire control systems [2–6]. It was also possible to develop the entire family of laser radiation sources with different spectral, energy and time characteristics. In addition, the research studies carried out on detection systems including systems of target observation, detection, identification and tracking (with use of the spectrum ranging from ultraviolet through terahertz) have led to the development of optoelectronic security systems, object control systems (including fire control), on-board data analysis systems, tracking warheads, training simulators and thermovision systems [7–9].

The examples of laser devices and laser technologies useful for military applications, developed at the Military University of Technology, which have been practically used in industry, environmental protection and medicine will be discusses in the following sections of the article. Presented examples of dual-use technologies of optoelectronics which include: modern laser sources, systems of radiation detection and transmission, are implemented, inter alia, in the medical devices for diagnostics and therapeutics, in the systems for contami-

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Table 1
The basic applications of laser devices in the systems of military technology

Applications	Examples of optoelectronic devices/systems
Distance measurement	Laser rangefinder
Target tracking	Laser systems for automatic target tracking
Target indication	Laser target illuminators Laser-guided bomb (LGB) Laser-guided bullet Bullet trajectory projections Passive tracking systems installed in homing missile warheads Passive detecting-tracking systems (IR search and track system, IRST)
Fire Control	Laser rangefinder with viewfinder
Observation, detection and target identification	Laser illuminators Laser radiation detection systems Passive systems of multispectral detection Integrated observation systems (range-finder camera + thermovision camera + low-level lighting camera) Laser scanners
Battlefield simulation	Laser shooting simulators of rifle, tank cannon, anti-tank and anti-aircraft cannons
Proximity fuses	Contactless laser fusers for bombs, projectiles or torpedoes
Navigation / Dead recognizing	Aircraft approach assisting laser systems Scanning laser locator used during aircrafts connections Laser altimeter Hydrografic laser system Laser systems for axis alignment Laser for engineering machinery guiding
Angular velocity measurement	Laser gyroscope
Gas velocity measurement	Laser anemometer
Atmosphere exploration	Laser radar for atmosphere monitoring Laser remote detection of chemical and biological warfare agents
Telecommunications	Laser link Satellite laser link Optical-fiber laser telecommunication
Visualization and data recording	Holography, information confidentiality, terrain awareness, 3D aerial photographs
Controlled thermonuclear fusion	Laser method of plasma heating and compression in a magnetic field (laser-focus) Laser method of plasma compression with detonative cumulative pre-compression
Nuclear power	Laser-isotope separation
Thermal or laser optical impact	Directed energy weapons, laser radiation weapon protection

nation detection and atmosphere pollution, in criminal investigation techniques and systems of industrial processes control [10–12].

2. Medical applications of lasers

Applications of laser in medicine are becoming more popular and are primarily focused on the radiation sources and the various systems of detection and imaging. The specific features of the lasers radiation include its high intensity, monochromatic characteristics and small divergence of beam angle. These parameters are playing particular role in medical applications and lasers have created new surgical opportunities, especially for laparoscopic and endoscopic treatments.

Due to the impact on the tissue, the lasers used in medical devices are often divided into high-energy (surgical) and low-energy (bio-stimulation) lasers. The high-energy lasers are used in the kits for tissue destruction or removal (cutting, evaporation and coagulation). The low-energy lasers are applied in pain therapy, sports medicine, dermatology, rheumatology and stomatology. The medical applications of lasers include also their use for photodynamic method of cancer diagnosis and therapy.

The effect of laser radiation is largely dependent on the tissue features (mainly on absorption) and the characteristics of laser radiation (wavelength, continuous or impulsive operation class) including the values of the laser output (i.e. density and value of power and energy) and exposure time (impulse length, frequency of replication). Depending on the power and time of the impact of laser radiation on the tissue the following mechanisms of laser-tissue interactions are observed: photo-chemical (photo-stimulation); thermal (coagulation, evaporation); photo-ablation (non-thermal tissue removal); and electromechanical (photo-destruction).

Photochemical responses are observed with the low level power values of laser radiation (< 10 mW/cm^2). This type of laser-tissue interaction is utilized in biostimulation and in the photodynamic therapy (PDT). The latter method relay on the selective oxidation of the biological material of the cancer tissue by singlet oxygen or radical species. The oxidation agents are generated from molecular oxygen, dissolved in the cells, and exogenous dyes (photosensitizer), which has better cumulative capacity in cancer tissues, by treatment with light of the suitable power and wavelength adjusted to the absorption bands of dye. This phenomena allows the selective destruction of cancer tissues, with concurrent preservation of the healthy ones. The method is used for the treatment of skin tumors, gynecological sphere, lungs, gullet, tongue, throat, stomach, bowels and urinary bladder as well. In the comparison with traditional methods of cancer treatment (e.g. surgery, exposition, chemotherapy) the PDT method is much more selective, generally well tolerated by human's organism, allows good cosmetic effects, can be used repeatedly and what important, can be combined with diagnostic methods. In the process of biostimulation the lasers of continuous action (He-Ne, 632.8 nm), the solid-state lasers (630 nm, 670 nm, 830 nm) as well as the pulsed solid-state lasers (904 nm) have been applied. The photodynamic method is utilizing the semiconductor lasers, operating at 405 nm and 630 nm, and the solid lasers (SHG YAG:Nd, 532 nm).

The thermal impact is observed for the lasers with the density of power higher than 1 W/cm^2. The impact effects are dependent on the temperature inside the tissue illuminated by the laser. The radiation of low-energy lasers generates the increase of the tissue temperature at the most of 0.1–0.5°C. In the case of the high-energetic lasers (up to 100 W) the temperature higher than 150°C is achievable. Among the many lasers used for generation of impact effect, the following devices are worth the mentioning, the carbon dioxide (CO_2) molecular laser, the argon laser (Ar) and the solid lasers (Nd:YAG). The argon laser coagulates the capillaries (H = 25–570 J/cm^2, $t = 0.5$ s; low depth of penetration); instead the solid laser (Nd:YAG) has ability to penetrate capillaries with greater diameter (H = 600–2000 J/cm^2, $t = 2$ s, penetration depth of 2–8 mm).

The effects of ablation usually can be found during the short laser pulses (the power density larger than 1 MW/cm^2), which affect the tissue with high value of absorption coefficient. As a result of laser impact (low depth of penetration, a few μm) the process of molecules dissociation is observed inside the tissue, leading to the rapid burst and ejection of cellular structures. The laser impact on tissues is short ranged and remaining part of the tissue remains not heated. The ablation method can be used for the removal of cancer tissue, blood vessels cleaning and blood clot removal, and in some cases, during ophthalmology treatments. In this method the following types of lasers are employed: TEA-CO_2, Er:YAG (2.9 μm), Ho:YAG (2.1 μm), Nd:YAG (1.06 μm), as well as the lasers with the wavelengths of 450–500 nm (dye lasers), 308 nm (XeCl-excimer) and 200 nm (193 nm ArF-excimer and 5th harmonic, 213 nm Nd:YAG).

The electromechanical interaction, also known as the photodestruction, usually occurs with very large power density values of laser radiation (100 MW/cm^2), and does not depend on the absorption coefficient of tissue. This interaction is usually implemented for the tissues characterized by the high level of transmission for laser radiation. In this case, high power laser pulse is focused on the small surface. In the area of focus, the extra-strong electric field can be found with value of 10^9 V/cm, which causes ionization of tissue. The mentioned above effect of mechanical laser action on the micro-area is mainly implemented in the micro-surgery of the anterior segment of the eye.

The research studies carried out on the use of lasers in medical devices and systems at the Military University of Technology have a long tradition. It is worth mentioning that a lot of the studies and implementations had its unique and pioneering character (the first ophthalmic coagulator in the World). The implementation of the photo-dynamic method in the cooperation with many clinics made the MUT one of the leading research centers for the cancer diagnosis and therapy.

Recently, the wide spectrum of medical diagnostic applications, especially in the cancer treatment, have found the laser induced fluorescence (LIF) spectroscopy [13–15]. Unlike the histopathological examination, the optical methods of biopsy are non-invasive, do not require the fine-needle aspiration biopsy, the amount of experimental material is unlimited, the laser radiation is carried by optical fiber, the measurement is conducted in a real time and the same workspace can be examined repeatedly. The LIF cancer detection method relies on the tissue fluorescence recording which is radiant with special fluorescent dyes present in the biological material and activated by the laser radiation. The phenomena of emission changes inside unhealthy tissues can be explained by the differences in the quantity and quality of fluorophors, the changes in their oxidation-reduction equilibrium, the depth position, their different contents of the absorbing but nonfluorescent chromosomes inside the cells, the changes of the out-cellulous matrix structure as well as the layers quantity of the cellular lining.

Outside the domain of medicine the fluorometric analyzers are applied in many other areas including, the environmental protection and crime detection. These devices allow for example, the detection of biological contamination, including the anthrax spores and microscopic traces of the explosive materials. The spectral radiation in the UV and blue light range corresponds to excitation maximum of many optical mediums, organic dyes, drugs, hazardous chemicals and biological materials. The laser sources of UV and blue radiation may be used, inter alia, for the detection of explosives.

In this way, the implementation of research and development in the area of instrumental support for medical and biological sciences contributed to the development of analytical methods, technologies and devices for detection of various security threats.

3. Lasers for security monitoring

The methods for security monitoring, from the perspective of the data acquisition, can be divided into two groups sampling at the risk location ("in situ") and the remote detection, identification and measurement of risk parameters [16]. In the first group of methods, due to the different time and place of sampling and analysis, accuracy and uniqueness of the measurements are not precise. The remote methods are free of the limitations mentioned before and depending on the applied measurement technology are capable of security monitoring even from a long distance (a few kilometers).

There are two types of systems used for remote monitoring of threats, a “stand-off” and a “remote”. The “stand-off” systems are capable to detect the threats (gases, aerosols, smoke, dusts) from a large distance without any contact with the polluted area. This type of systems includes active laser systems (LIDARs) [17] or passive thermo-vision systems with employment of the narrow filters, which are especially well matched to the bands of gases absorption and are capable to visualize the changes of absorbed radiation along the way of gas distribution [18]. The single “stand-off” base station may cover a substantial area, which size depends on the range of sampling radiation, the field of vision and the scanning speed.

The “remote” systems use the various types of minor point sensors, and the data from these sensors is sent through the wired or wireless links to emergency centers. It should be noted, that in this case the contact of a sensor with a sampling area is necessary. The remote detection is achieved due to the systems of measured data transmission [19].

In recent years, the optoelectronic techniques, in particular based on the methods of laser spectroscopy, have been developed intensively. The research efforts are focused on the development of a very sensitive optical sensors for the detection of chemical and biological warfare agents and high-energy explosives. Additionally, the optoelectronic devices for thermal, seismic, electromagnetic and other hazards will be developed and implemented as well.

The variety of biological toxic agents i.e. bacteria, viruses and toxins makes it necessary to use the various detection systems of biological threats. In most of these systems the optoelectronic methods are implemented. For these purposes the UV lasers inducing fluorescence (LIF) are used (range from 248 nm to 355 nm). In this type of devices the biological aerosol is lighted by the pulse UV laser. Consequently, the radiation causes the fluorescence effect of the fluorophores contained in the biological material, tryptophan (Trp), tyrosine (Tyr), phenylalanine (Phe), NADH and FAD.

The examples of applying fluorescence spectroscopy to characterization of chemical and biological agents are presented in Figs. 1 and 2. Figure 1 shows the example of three-dimensional fluorescence spectrum of SEMTEX (explosive material), which has been clearly defined for the various wavelengths of activation. Figure 2 presents the results of excitation-emission characteristics measurement of tryptophan (one of the 20 standard amino acid building proteins). The characteristic fluorescence spectra of SEMTEX and tryptophan activated by laser radiation with wavelength of 350 nm allow to detect and identify these substances even remotely. This is possible because of high sensitivity and selectivity of this method.

Since many years the work on the remote laser sensing have been conducted at the Military University of Technology both at the basic research level as well as at the applied research level including design, prototyping and constructions of sensing systems. The fluorescence/depolarization LIDAR for chemical and biological substances detection in the air, which was designed and built at MUT is shown in Fig. 3. The spectral signals of fluorescence are recorded in 32 spectrum channels in the term of the spectrum shape. This shape constitutes the unique “fingerprint” of chemical or biological material and makes its detection and categorization possible.

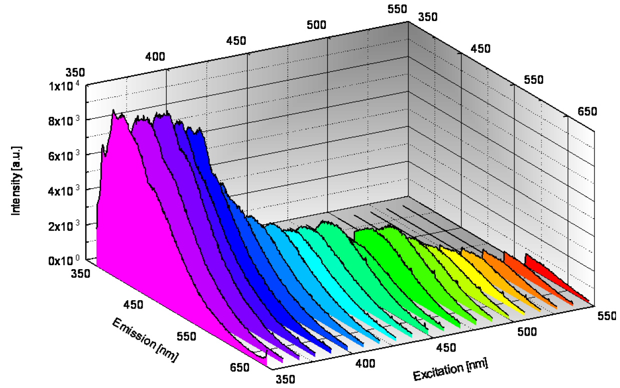

Fig. 1. The three-dimensional fluorescence spectrum of SEMTEX

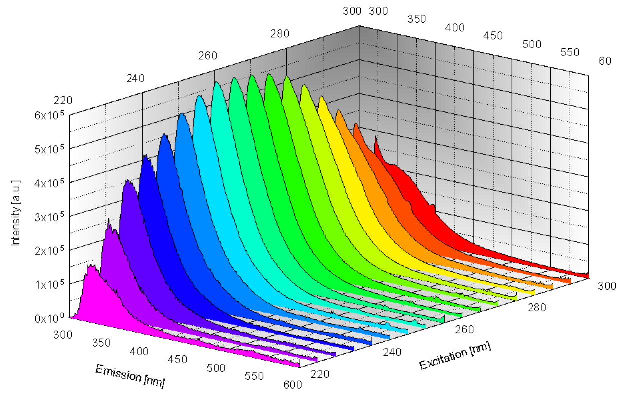

Fig. 2. Excitation and emission characteristics of tryptophan

Fig. 3. Fluorescence/depolarization LIDAR for mid-range stand-off detection of the chemical and biological threats in the air

As the another example of a practical application of the laser telemetry the laser speedometer can be given. As a result of conducted research studies the prototype of the laser speedometer has been developed. Its range of activity is up to 1000 m, the measured speed is ranging from 0 to 250 km/h, more importantly, the laser transmitter has an eyes-proof class.

The hazard accidents associated with explosions of improvised explosive devices (IEDs) as well as risks connected with possibilities of their use during the terrorists attacks present a great problem and threat in the modern world. The scale of such risks can be reduced by quick detection of an explosive material installed inside these devices. Explosives detection is a very important analytical problem and has become the most important in many domains of science and economy. In some of the airport terminals the special check-points, using the ion mobility spectrometry (IMS) capable to detect explosives, have been already installed.

In general, many explosive material have low vapor pressure and are difficult to detect due to their very low concentration in the air. However, explosive materials tend to decompose with emission of certain type of gases. The knowledge about the nature and concentration of these gases, which are products of explosives decomposition, makes possible their detection with specific gas sensors. Explosives containing nitrogen atoms in their structure upon degradation emit trace amounts of nitric oxides, i.e. N_2O, NO, NO_2 [20, 21]. The explosives detection is carried out mainly by using methods based on the physical characteristics assessment. These characteristics make possible to differentiate explosives out of other substances. The attributes such as the wavelength of electromagnetic radiation absorbed or emitted by material, the ability of ionization breakdown to specific ions, the ability of selective sorption on absorbent surface and the light refractive index could be specified.

4. Lasers in the industrial processes monitoring

Currently developed optical sensors of gaseous atmospheric contaminants have been used in the hybrid multi-sensor systems of permanent monitoring of industrial processes. Usually these systems contain the optical sensors for detection of: O_3, SO_2, NO_2, CO, CH_4 (optical sensors); NO_2, NO, H_2S, CO, NH_3 (solid-state sensors); O_2, O_3, SO_2, NO, CO, CO_2, HCl, HF (electro-chemical sensors); and CO_2, CO, SO_2, H_2S, C_nH_m, C_6H_5-R (photo-acoustic sensors). The system includes the functional modules, which are configured to fit precise research and assay need. This system can be also equipped with additional sensors of specific gases, measurement capabilities, a system of transmission and data processing.

The systems enable continuous monitoring of gaseous pollutants emitted for instance by energetic companies, power and thermal power stations, chemical plants, incineration plants of municipal, hazardous and hospital wastes, petrochemical industry and refineries, cement works, calcic works and paper industry. The currently available systems allow for constant monitoring of atmosphere in the open air (car fumes analysis) as well as continuous air analysis in closed facilities.

5. Lasers in environmental protection

The basic goals of environment monitoring include providing information of current contamination status of the particular environmental components, providing the data on the volume pollutants expelled into the environment in the controlled or accidental manner, and the forecasting of threats proliferation. The great dynamic of air mass makes it the main way of contamination spreading and its transportation into water and soil. Due to the dynamics of air mass circulation and consequently the potential risk of population exposure to its contamination, the air monitoring has priority over the monitoring of other environment components, such as hydrosphere and lithosphere. It should be mentioned, that in the case of atmosphere as opposed to water and soil, there is no possibility of contamination isolation.

The necessity of simultaneous detection of combat chemical weapons and toxic industrial hazards constitutes the important advantage of the modern concepts of environment monitoring. The chemical industry on the Earth holds the great volume of industrial toxic components. Usually, there are a lot of raw materials and semi-products for synthesis (e.g. chlorine, ammonia, hydrogen sulfide, methyl isocyanine, phosgene) and final products (e.g. pesticides). These substances have a level of toxicity comparable to the old type of chemical weapons and some of them were actually used as a such weapon (i.e. phosgene, hydrogen cyanide). The lack of technical possibilities of quick detection of pollution and definition of the current and potential polluted areas in case of any failure or sabotage with use of toxic industrial hazards has a potential of great human losses and carries the losses among the rescue services. The passive or active laser systems operating in IR range are the example of the systems, which can provide the quick response in case of accidents regarding release of toxic chemicals.

The another device developed at MUT, which is suitable for environmental applications is reflectance profilometer, device suitable for 3D terrain imaging. The profilometer is designed and dedicated for unmanned aerial platforms and has the ability to analyze the attributes of terrain coverage invisible for naked eye or in analysis of typical satellite pictures. The measurement is carried out for three selected wavelengths simultaneously. As the result of measurements, in addition to the typical 3D representation of a terrain's surface, the spectral elevation model is also obtained. This model allows terrain's map modeling which reflect its reflectance characteristics, and strictly speaking, its overlaying elements (buildings, greenery, soil, roads, rivers, etc.). The analysis of this type of maps makes possible to track objects such as camouflaged objects and vehicles, locations of buried objects (i.e. mines and traps). The analysis can be also used for monitoring of the vegetation status, in order to specify the type of crops, or finally for validation of the terrain's changes (change-detection method), i.e. by comparison of old and current maps status. The results of imaging based on analysis of terrain's reflection characteristics obtained by the reflectance profilometer are shown in Fig. 4.

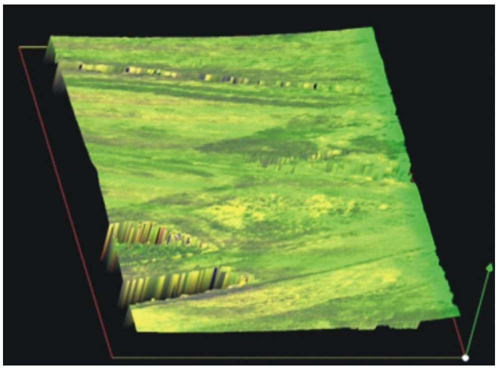

Fig. 4. The 3-D terrain map obtained from reflectance profilometer measurement carried out during the unmanned aerial platform flight

6. Summary

On the basis of the research studies currently carried out and the observed market trends around the world, considering the economic potential of different technologies and their contribution into solving social problems and the high level of knowledge they require, to the most important strategically supportive key technologies belong nanotechnology, micro- and nano-electronics, photonics, advanced materials and biotechnology. These key technologies have the "horizontal" character, because they can interpenetrate trough the technologies of all sectors. They often link to different areas of science and use the interdisciplinary or convergent approach, anticipating that this situation can lead to innovations that can contribute to many problems of today's society to be solved.

The key technologies simultaneously have a character of dual-use technologies, which can be used not only within industry domains of military and defense, but also in different areas of advanced industrial and environmental technologies. These technologies include specialized test and research equipment, mechatronics technologies and control systems for manufacturing and working processes support, advanced materials and nanotechnologies, as well as technical systems supporting their engineering design and implementation, proecological technologies, rationalization of the raw materials consumption, renewable energy, and technologies of technical and environmental safety.

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