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Experimental researches of dynamic spectral processing of optical radiation in the active electro-optical system

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Abstract. The process of dynamic spectral processing of optical radiation in the active electro-optical system that provides enhancement of the contrast of the image target has been experimentally researched. A routine of experiment and a diagram of an experimental setup have been developed. The sources of optical radiation in the transmitting part of the active electro-optical system were three semiconductor lasers operating in the ranges of the red, green, and blue spectral regions. Absorption optical filters were used in the experiment as the elements simulating the spectral properties of the reflecting surfaces of the target and the background. To enhance the contrast of the target image, the spectral composition of the laser radiation is formed to provide maximum suppression of the background signal with minimum attenuation of the optical signal of the object. When forming the spectral density of the laser radiation intensity, *a priori* information about the spectral characteristics of the target and the background has been used. The results obtained in the course of the experiment confirm the possibility to separate the target signal from the background interferences due to using the dynamic spectral processing of optical radiation in the active electro-optical system.

Keywords: active electro-optical system, dynamic spectral processing, image contrast.

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1. Introduction

All electro-optical systems can be separated into the passive and active ones according to the principle of formation of information fields (radiation fields). The passive electro-optical systems use information fields generated by natural radiators in the space of objects. An active method of constructing electro-optical systems involves creation of an information field by artificial radiation sources with further processing of their signal in the received channel.

Development of active electro-optical systems (AEOS) is of increasing interest and is caused, first of all, by the improvement of technologies for creating reliable and affordable laser radiation sources [1]. These systems are widely used in various fields (military and security, remote sensing, medicine, robotics, *etc.*) and often become an alternative to passive electro-optical systems and microwave radars.

One of the promising directions in the development of active electro-optical systems is creation of active spectral imaging systems that ensure detection and recognition of objects by their spectral features [2]. In these systems, either a broadband [3–5] or a tunable [6–8] laser is used as a radiation source, and the signal reflected from the surface under study is processed using a hyperspectrometer [3–5] or conventional camera [6–8]. Signal processing used in these systems is carried out in the post-detector area. It means that, at first, the reflected optical signal is decomposed into spectral components by using a dispersive element, and then radiation is recorded in spectral channels and converted into electrical signals, and digitized.

This article is devoted to experimental studies of the process of dynamic spectral image processing in an active electro-optical system. The feature of this class of systems is that they implement controlled spectral processing of optical signals in the pre-detector area. It's presumed [9], that if the processing is carried out in the optical range without converting signals into electrical ones, then it enables to eliminate errors arising in the course of conversion and opens up the possibility of the parallel processing of large information massifs.

It is worth to mention that electro-optical systems with the dynamic spectral processing of optical radiation of both passive and active types are analog optical computing devices, in which the dot product of a vector by a vector is realized [10]. The difference is that in passive systems with dynamic spectral processing the multiplication operation is implemented using optical element with controlled transparency. The dot product in active electro-optical systems with dynamic spectral processing is realized through changing the radiance of the spectral components of the illuminating light flux at known values of the spectral reflectance of the observed surface.

The principles of constructing active electro-optical systems with the dynamic spectral processing of optical radiation are described in [10, 11]. The work [11] outlines the principles of constructing AOES, providing enhance of the contrast of the target image. AOES that provides automatic detection of the target optical signal entering its input is considered in [10]. It is assumed that the source of radiation in these systems is a set of laser emitters with different operation wavelengths. The dynamic spectral processing in the systems under consideration is implemented by illuminating the observed scene with laser radiation, the spectral density of which is formed to maximally suppress the background signal at the AOES output with minimal attenuation of the signal reflected from the target. Formation of the spectral composition of laser radiation is based on *a priori* information about the spectral characteristics of target and background signals.

The analysis of scientific researches has shown that the work [12] is the closest to the present one. It represents the results of laboratory studies aimed at a prototype of an active hyperspectral system for detecting concealed targets. The system includes a radiation source, which is a fiber Raman emitter with microlaser pumping, which provides emission of a subnanosecond pulse in the visible and near infrared ranges. The receiving part of the system, which is designed to form hyperspectral images, includes a diffraction grating. Detection of radiation in the spectral channels is created using a CCD array. It should be noted that the system assumes the post-detector signal processing to detect concealed targets.

The purpose of this article is to summarize the results of experimental studies of the dynamic spectral processing of optical radiation in the active electro-optical system to provide the enhancement of the contrast of the target images.

2. Dynamic spectral processing of optical radiation in active electro-optical system

Let us consider an active electro-optical system with dynamic spectral processing of optical radiation and show that the optical signal arriving at its radiation receiver is the scalar product of the input signal vector and the vector of its instrumental function. We will also show how to determine the instrumental function of AEOS, which provides the enhancement of the contrast of the target image using the vector representation of optical signals.

Accordingly, AEOS includes a controlled source of polychromatic radiation, consisting of *m* monochromatic emitters (lasers) different in their spectrum. The spectral radiance $L_{\Sigma e}(\lambda)$ of the polychromatic radiation source is formed as the sum of the spectral radiances $L_{ek}(\lambda)$ of monochromatic emitters:

$$L_{\Sigma e}(\lambda)=\sum_{k=1}^{m} L_{ek}(\lambda)=\sum_{k=1}^{m} A_k \varphi_{ek}(\lambda), \tag{1}$$

where A_k is the weighting coefficient of the spectral radiance of the *k*-th radiation source; $\varphi_{ek}(\lambda)$ is the spectral radiance of the *k*-th source at $A_k=1$.

Since in (1) the spectral radiance $L_{\Sigma e}(\lambda)$ is the sum of a finite number of monochromatic components, the expression for the radiant flux entering the AEOS radiation receiver can be represented in the following form [10]:

$$\Phi_e = q\sum_{k=1}^{m} f_k x_k \cong \vec{F}^T \vec{X}, \tag{2}$$

where $q=\frac{\pi D^2{}_{out}\, S_{rr}}{16 l^2}\cdot\left(\frac{D_{in}}{f'}\right)^2$ is a parameter that depends on the distance to the probed surface *l* and the design parameters of AEOS (D_{out} is the diameter of the exit pupil of the optical system of the radiation source; D_{in}, f' are the diameter of the entrance pupil and the focal length of the optical system of the receiving channel of AEOS [13]; S_{rr} is the area of the radiation receiver); $\vec{F}=\left[f_1,\ldots f_k,\ldots f_m\right]^T$ is the vector of the AEOS instrumental function, the coordinates of which are equal to the maximum values of the spectral radiances of the monochromatic components of the AEOS radiation source, $f_k=A_k$; $\vec{X}=\left[x_1,\ldots x_k,\ldots x_m\right]^T$ is the vector of the input optical signal, the coordinates of which correspond to the radiant fluxes entering the input of the AEOS receiver for each monochromatic component of the radiation source:

$$x_k = q\int_{\lambda_{min}}^{\lambda_{max}} \varphi_{ek}(\lambda)\tau_{o1}(\lambda)\tau_m^2(\lambda)\rho(\lambda)\tau_{o2}(\lambda)d\lambda, \tag{3}$$

where $\tau_m(\lambda)$ is the spectral transmittance of the medium [13]; $\tau_{o1}(\lambda)$, $\tau_{o2}(\lambda)$ are the spectral transmittances of the optical systems in the transmitting and receiving channels of AEOS; $\rho(\lambda)$ is the spectral reflectance of the probed surface (with diffuse reflection) [13]; $\lambda_{min}\ldots\lambda_{max}$ is the operation range of wavelengths of AEOS.

Thus, the signal recorded by the radiation detector of the active electro-optical system with dynamic spectral processing is the scalar product of the vector $\vec{F}$ of its instrumental function by the vector $\vec{X}$ of the input optical signal that represents the spectral properties of the reflecting surface.

Using the vector representation of optical signals, we define the AEOS instrumental function that provides the maximum contrast of the image of a homogeneous target on a homogeneous background at its output. Let us assume that the signal of a homogeneous target is characterized by a vector $\vec{T}$, and the optical signal of a homogeneous background is characterized by a vector $\vec{B}$ (Fig. 1).

The vector of the AEOS instrumental function $\vec{F}$, which ensures the maximum increase in the contrast of the object image at its output, must be orthogonal to the background vector $\vec{B}$ and lie in the plane passing through the vectors $\vec{T}$ and $\vec{B}$. This vector is defined as follows [11]:

$$\vec{F} = r\left(\vec{T} - N\cdot\vec{B}\right), \tag{4}$$

where $N = \vec{T}^T\vec{B}/\vec{B}^T\vec{B}$ is the projection of the target vector $\vec{T}$ onto the base vector of the background vector $\vec{B}^o = \vec{B}/\sqrt{\vec{B}^T\vec{B}}$, normalized to its length $\left\|\vec{B}\right\| = \sqrt{\vec{B}^T\vec{B}}$; r is the normalizing factor that maximizes the optical signal recorded by the radiation receiver:

$$r = 1/\max_i\left(t_i - N\cdot b_i\right),$$

where t_i and b_i are the coordinates of the target and background vectors, respectively.

Thus, using the vector representation of the optical signals of the target and the surrounding background, the instrumental function of AEOS is determined. It provides the enhancement of the contrast inherent to the target image. The vector of the AEOS instrumental function must be orthogonal to the background vector $\vec{B}$ and lie in the plane passing through the target $\vec{T}$ and background $\vec{B}$ vectors, respectively.

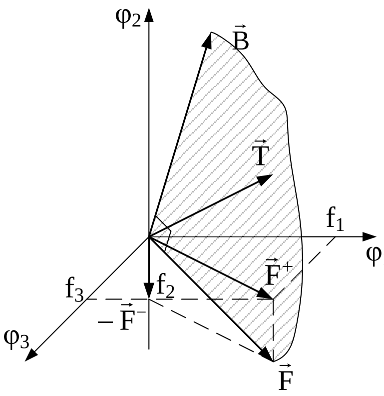


Fig. 1. Vector representation of the dynamic spectral processing of optical radiation in AEOS.

3. The experimental setup diagram

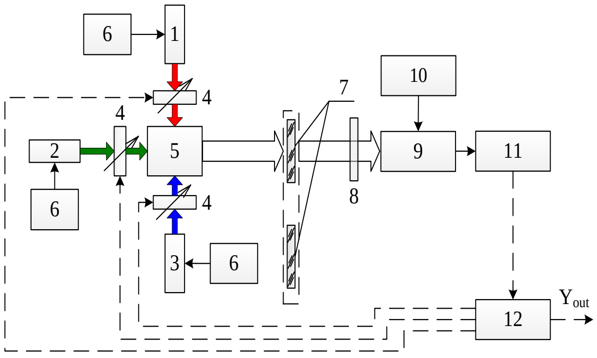


Fig. 2. Block diagram of the experimental setup.

The block diagram of the experimental setup is shown in Fig. 2. It consists of transmitting and receiving units, as well as a device for forming the reflected optical signal of the target and background.

The transmitting unit includes:
- laser, radiation wavelength λ = 635 nm (*1*);
- laser, radiation wavelength λ = 532 nm (*2*);
- laser, radiation wavelength λ = 450 nm (*3*);
- three attenuators (*4*), providing control of the laser radiation intensity;
- dichroic prism (*5*) for spatial combination of laser radiation into one beam;
- three power supplies for lasers (*6*).

The device providing formation of the reflected optical signal includes a pair of absorption filters (*7*), simulating the reflective properties of the “target” and “background”.

The receiving unit includes:
- neutral-density filter (*8*);
- photomultiplier tube (*9*) with power supply unit (*10*);
- microammeter (*11*);
- electronic computer (*12*).

In the diagram (Fig. 2), curly arrows indicate the passage of optical radiation. Solid lines with arrows in the diagram show the passage of electrical signals, and dashed lines with arrows conventionally show actions that were carried out in the manual mode. These actions include transferring current values from the output of the photomultiplier tube to the computer memory, adjusting the transmittance of the attenuators, and generating a signal at the output of AOES.

The attenuators that were used to vary the power of the lasers consisted of a pair of polarizing filters. To receive and measure optical signals in the experiment, we used the FEU-51 photomultiplier tube, which was powered by a special high-voltage unit. To measure the current at the photomultiplier tube output, a UNI-T M890G universal digital multimeter was used, and it was connected to the FEU-51 anode circuit in series with its voltage divider.

4. Methodology of the experiment

During the experiment, two sets of absorption optical filters were used to form the reflected optical signals of the target and the background.

First set:

- background – OG-11 (orange glass);
- target – YGG-11 (yellow-green glass).

Second set:

- background – VG-6 (violet glass);
- target – BG-2 (blue glass).

In the first set, optical filters simulating the background and target signals had approximately the same spectral transmission characteristics at the operating wavelengths of the lasers that were used in the experiment. The filters of the second set had spectral characteristics that differ significantly.

The choice of optical filters was based on the calculation of their spectral transmittance. The calculation was carried out using information about the extinction coefficient of optical filters, placed in the catalog of colored glasses [14]. When calculating the spectral transmittances, the reflection from the surfaces of the optical filters was also taken into account.

The spectral transmittance $\tau(\lambda)$ of optical filters with a thickness l (mm) at the normal incidence of light was calculated using the following expression [14]:

$$\tau(\lambda) = (1-\rho)^2 \cdot 10^{-k(\lambda)l} ,$$

where $k(\lambda)$ is the spectral extinction coefficient of optical filter glass; ρ is the reflectance determined using the Fresnel equation [10]:

$$\rho = \left(\frac{n-1}{n+1}\right)^2 ,$$

where n is the refractive index of the glass.

The calculated dependences of the spectral transmittance on the wavelength for four light filters are shown in Fig. 3. The vertical dashed lines in Fig. 3 show the monochromatic radiation of three lasers that were used in the experiment.

The experimental procedure included the following stages:

1. Measurement of the spectral characteristics of the target and background.
2. Calculation of the vector of the instrumental function, providing enhancement of the contrast of the target image.
3. Dynamic spectral processing of optical radiation and the record of background and target optical signals.

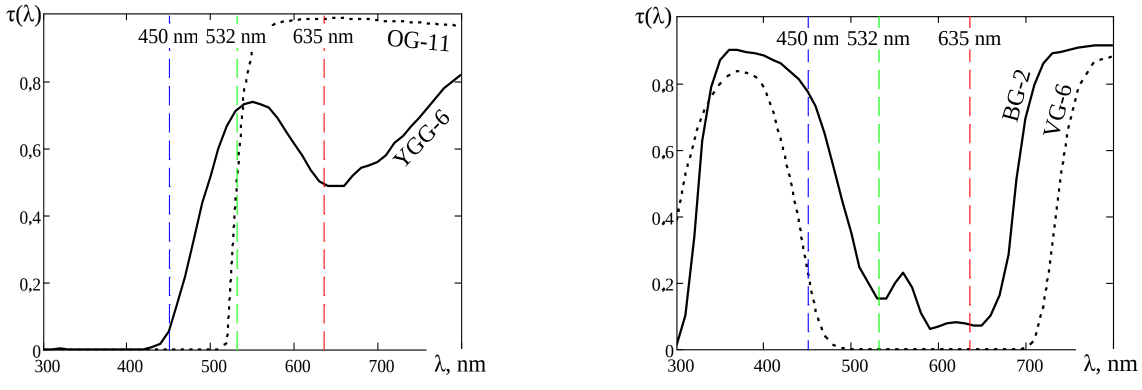
Stage 1. Measurement of the spectral characteristics of the target and background.

The spectral characteristics of the target and the background were measured by sequential turning on the lasers and recording the signal at the output of PMT, first for an optical filter simulating the target, and then for an optical filter simulating the background. As a result, the target vector $\vec{T} = [t_B, t_G, t_R]^T$ and the background vector $\vec{B} = [b_B, b_G, b_R]^T$ were formed, the coordinates of which were the current values measured at the PMT output when the corresponding laser was turned on.

The spectral features of the target and the background measured in the course of experimental studies, which were simulated by pairs of optical filters YGG-6/OG-11 and BG-2/VG-6, are shown in the form of graphs in Fig. 4. On these graphs on the abscissa axis the wavelengths values of the laser radiation are plotted, and on the axis of ordinates the current values in the anode circuit of PMT-51 are represented.

Stage 2. At this stage, the calculation of the vector of the instrumental function $\vec{F} = [f_R, f_G, f_B]^T$, which provides the enhancement of the contrast of the target image at the output of an active electro-optical system with the dynamic spectral processing, was performed. The vector of instrumental function was calculated using the expression (4). This calculation used information about the spectral features of the target and background, obtained at the first stage.

The calculated vectors, which provide complete suppression of the background signal with minimal attenuation of the target signal, are shown in the form of bar diagrams in Fig. 5. In these diagrams, on the abscissa axis the wavelengths values of the laser radiation are



a) b)

Fig. 3. Dependences of the spectral transmittance of a pair of light filters that simulate the optical signals of the target and the background: a) YGG-6 (solid line) and OG-11 (dashed line); b) BG-2 (solid line) and VG-6 (dashed line).

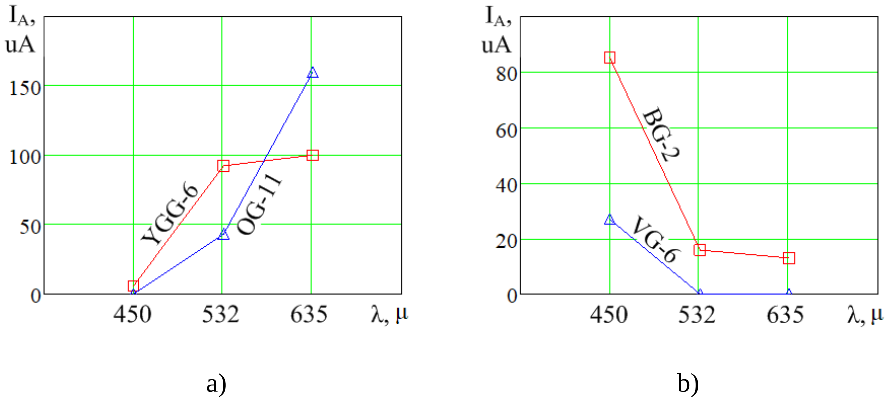


Fig. 4. Spectral features of the target and background, which are simulated by a pairs of optical filters: YGG-6/OG-11 (a) and BG-2/VG-6 (b).

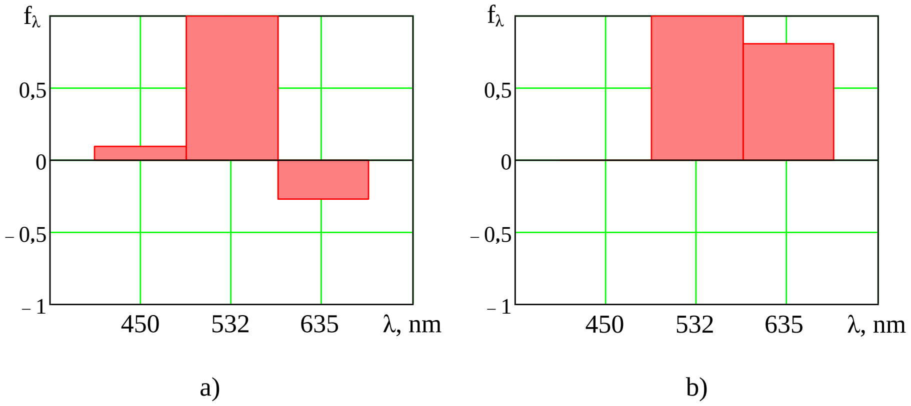


Fig. 5. Coordinates of the instrumental function vector, providing the enhancement of the contrast of the target image, by using a pair of optical filters: YGG-6/OG-11 (a) and BG-2/VG-6 (b).

plotted, and on the axis of ordinates the values of the corresponding coordinates of the instrumental function vector are displayed. It should be noted that the coordinates of the instrumental function vector correspond to the transmission coefficients of the laser radiation attenuators installed in the transmitting part of the experimental setup.

After calculating the instrumental function vector $\vec{F}=\left[f_R, f_G, f_B\right]^T$, the vectors $\vec{F}^+$ and $\vec{F}^-$ were formed, the geometric meaning of which is shown in Fig. 1.

Stage 3. At this stage, the dynamic spectral processing of optical radiation was carried out. It consisted of adjusting the attenuators, recording the radiation of the target and background, and calculating the output signal.

To do this, first of all, the transmittance of the laser radiation attenuators were adjusted to the coordinates of the vector $\vec{F}^+$, and the radiation of the target and the background was recorded:

$$Y_T^+ = \vec{F}^{+T}\vec{T};$$

$$Y_B^+ = \vec{F}^{+T}\vec{B}.$$

Then this procedure was repeated for the vector $\vec{F}^-$:

$$Y_T^- = \vec{F}^{-T}\vec{T};$$

$$Y_B^- = \vec{F}^{-T}\vec{B}.$$

After that, the signals for the target Y_T and the background Y_B were calculated at the output of the active electro-optical system by subtracting the corresponding values that were measured for the vectors $\vec{F}^+$ and $\vec{F}^-$:

$$Y_T = \vec{F}^{+T}\vec{T} - \vec{F}^{-T}\vec{T};$$

$$Y_B = \vec{F}^{+T}\vec{B} - \vec{F}^{-T}\vec{B}.$$

The values of the target Y_T and the background Y_B signals obtained in the course of experimental studies at the output of the active electro-optical system are adduced in Table. This table also shows the values of the target and background output signals, which were obtained at the absence of dynamic spectral processing. In this case, the transmittances of all laser attenuators were equal to unity.

Table. Results of experimental studying the dynamic spectral processing of optical radiation in the active electro-optical system.

No	Without processing		With processing		Contrast ratio
	Y_T, μA	Y_B, μA	Y_T, μA	Y_B, μA	
1	198	203	66	1	78
2	114	27	30	0	1.6

The efficiency of dynamic spectral processing in AEOS was estimated by comparing the contrast values of the target at its output with and without processing. Target contrast was calculated using the following expression:

$$K = (Y_T - Y_B)/(Y_T + Y_B).$$

When using a pair of YGF-6 and OF-11 optical filters to simulate the target and background signals, the contrast at the AEOS output without the use of dynamic spectral processing was $K \cong -0.01$, and when the dynamic spectral processing was used – $K = 0.97$. When using a pair of BG-2 and VG-6 optical filters, the contrast values of the target without processing and in the case of applying processing were equal to $K \cong 0.62$ and $K = 1$, respectively.

Thus, the results obtained in the course of experimental studies show that applying the dynamic spectral processing of optical radiation enables to suppress the background signal at the output of AEOS almost completely and to minimize the signal of the object. It provides the enhancement of contrast in the first case (a pair of YGG-6/OG-11 optical filters were used, the spectral features of which were significantly different) approximately to 78 times, and in the second case (a pair of BG-2/VG-6 optical filters were used, the spectral features of which were practically equal) – more than 1.5 times.

5. Conclusions

The possibility of performing the dynamic spectral processing of optical radiation in the active electro-optical system, which provides enhancing the contrast of target image, has been experimentally ascertained. The sources of optical radiation in the transmitting part of the active electro-optical system were three semiconductor lasers operating in the ranges of red, green and blue spectral ranges. Absorption optical filters were used as elements simulating the spectral properties of the reflecting surfaces of the target and the background. The efficiency of spectral processing of optical radiation in the active electro-optical system was determined by the contrast value with the application of processing or without it. It has been shown that as a result of dynamic spectral processing of optical radiation, it is possible to enhance the contrast of the target image, both in the case of the approximate equality of spectral features of the target and the background, as well as in the case when they differ significantly.

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Goorin O.A.: Investigation, Data Curation.
Biesova O.V.: Visualization, Resources.

Експериментальні дослідження динамічної спектральної обробки оптичного випромінювання в активній оптико-електронній системі

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Анотація. Експериментально досліджується процес динамічної спектральної обробки оптичного випромінювання в активній оптико-електронній системі, яка забезпечує підвищення контрасту зображення. Розроблено методику проведення експерименту та схему експериментальної установки. Джерелами оптичного випромінювання в передавальній частині активної оптико-електронної системи служили три напівпровідникових лазери, які працювали в діапазонах червоної, зеленої та синьої ділянок спектра. Як елементи, що імітували спектральні властивості відбивальних поверхонь об’єкта та фону, в експерименті застосовувалися абсорбційні світлофільтри. Для підвищення контрасту зображення об’єкта спектральний склад лазерного випромінювання формувався таким чином, щоб забезпечити максимальне заглушення сигналу фону з мінімальним ослабленням оптичного сигналу об’єкта. При формування спектральної густини інтенсивності лазерного випромінювання використовувалися апріорні відомості про спектральні характеристики об’єкта спостереження та фону. Отримані в ході експерименту результати підтверджують можливість виокремлення сигналу об’єкта з фонових перешкод шляхом застосування процесу динамічної спектральної обробки оптичного випромінювання в активній оптико-електронній системі.

Ключові слова: активна оптико-електронна система, динамічна спектральна обробка, контраст зображення.