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OPTICAL SIGNAL PROCESSING

Optimal Processing of Noisy Images in a Photodetector with Limited Dynamic Range

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Abstract—A study aimed at optimizing noisy image processing under conditions of strong additive noise has been performed. An algorithm of optimal signal processing was developed and a possibility of improving image quality due to the subtraction of excess additive noise (which limits the photodetector dynamic range) was substantiated. The possibility of technical implementation of noise subtraction due to forced recombination of charge carriers in the photodetector is experimentally confirmed. The proposed approach to design processing systems makes it possible to improve the quality of recorded images under noisy conditions without any changes in the photodetector design.

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1. INTRODUCTION

The limitation of photodetector dynamic range affects significantly recording optical signals and measurement of their parameters in the case of strong additive noise [1]. Under these conditions, the conventional algorithms and methods for processing received signals, which are designed to solve a number of important applied problems related to the detection and recognition of objects of different physical nature, turn out to be inefficient. This circumstance makes researchers to search for ways of expanding the dynamic range of modern photodetectors and to raise the upper boundary of illuminances recorded.

In recent years, much attention has been paid to the development of methods aimed at direct processing noisy optical images, which make it possible to suppress noise on optical carrier or in input optoelectronic units of detection systems, the limitation of the dynamic range of which is most important. In this study, we considered some methods proposed by us, which provide dynamic range expansion for video photodetectors under conditions of intense additive noise, and experimentally checked their operating capacity.

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2. ALGORITHM FOR PROCESSING NOISY IMAGES WITH ALLOWANCE FOR LIMITATION OF PHOTODETECTOR DYNAMIC RANGE

In most of modern photodetectors characterized by charge accumulation, the limitation of dynamic range occurs for the following reasons [2]:

(i) finite capacitance of photodetector resolution elements, which affects the charge that is generated under illumination and accumulated in the semiconductor layer of the photodetector;

(ii) incomplete recording of the accumulated charge formed in the semiconductor layer of the photodetector under illumination.

The output signal of photodetector is formed as a result of conversion of the input flux of light photons, distributed in the general case according to the Poisson law [3], into a flux of charge carriers (electrons or holes) in the semiconductor and their accumulation in the semiconductor layer of the photodetector, as well as the recording (as a result of recombination) accumulated charges generated by the signal + noise additive mixture, arriving at the photodetector, by an artificially formed flux of charge carriers with opposite sign.

The statistical distribution of the resulting carrier flux, with allowance for the effect of the aforementioned factors on the limitation of photodetector dynamic range, can be described by discrete difference-Poisson distribution in the form

$$P_{\mathrm{s+n}}(N) = \left[\frac{\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}})}{\bar{N}_{\mathrm{r}}}\right]^{N} I_N\left(2\sqrt{\left[\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}})\right]\bar{N}_{\mathrm{r}}}\right)\exp\left\{-\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}\right]\right\} \tag{1}$$

for the signal + noise additive mixture arriving at the photodetector. When only additive noise is detected, the statistical distribution of the resulting carrier flux has the form

$$P_{\mathrm{n}}(N) = \left(\frac{\bar{N}_{\mathrm{n}}}{\bar{N}_{\mathrm{r}}}\right)^{N} I_N\left(2\sqrt{\bar{N}_{\mathrm{n}}\bar{N}_{\mathrm{r}}}\right)\exp\left[-(\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}})\right], \tag{2}$$

where $I_N(\cdot)$ is a modified Nth-order Bessel function of the first kind; $\bar{N}_{\mathrm{s}}$, $\bar{N}_{\mathrm{n}}$, and $\bar{N}_{\mathrm{r}}$ are the mean numbers of charge carriers in the photodetector, generated, respectively, by the signal, additive noise (background), and the reading carrier flux during the accumulation interval T_{A}; and $\beta(\bar{N}_{\mathrm{n}})$ is the photodetector transfer coefficient, which takes into account the effect of the finite capacitance of photodetector element on the amount of accumulated charge.

With allowance for (1) and (2), the expressions for the likelihood ratios at the output of the optimal detector and its logarithm can be written in the form [4]

$$\Lambda = \frac{P_{\mathrm{s+n}}(N)}{P_{\mathrm{n}}(N)} = \frac{\exp\left\{-\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}\right]\right\}\left[\dfrac{\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}}}{\bar{N}_{\mathrm{r}}}\right]^{N} I_N\left\{2\sqrt{\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}}\right]\bar{N}_{\mathrm{r}}}\right\}}{\exp\left[-(\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}})\right]\left(\dfrac{\bar{N}_{\mathrm{n}}}{\bar{N}_{\mathrm{r}}}\right)^{N} I_N\left(2\sqrt{\bar{N}_{\mathrm{n}}\bar{N}_{\mathrm{r}}}\right)}, \tag{3}$$

$$\ln\Lambda = -\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \frac{\bar{N}_{\mathrm{r}}}{2}\left(\frac{\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}})}{\bar{N}_{\mathrm{n}}} + 1\right) + \ln I_N\left(2\sqrt{\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}}\right]\bar{N}_{\mathrm{r}}}\right) - \ln I_N\left(2\sqrt{\bar{N}_{\mathrm{n}}\bar{N}_{\mathrm{r}}}\right). \tag{4}$$

An analysis of expression (4) shows that the sum of its first and second terms reproduces (accurate to the constant factor and coefficient $\beta(\bar{N}_{\mathrm{n}})$) the structure of the relation describing the well-known algorithm for detecting signals at the photodetector output when the resulting charge carrier flux obeys Poisson's distribution [5]. One can pass from expression (4) to the relation describing the well-known algorithm for detecting signals in the case of Poisson's distribution when the conditions $\beta(\bar{N}_{\mathrm{n}}) \to 1$ and $\bar{N}_{\mathrm{r}} \to 1$ are satisfied. The physical meaning of these conditions is the implementation of necessary procedures in order to remove the factors limiting the photodetector dynamic range.

To determine the aforementioned procedures, we will approximate the difference-Poisson distribution by a normal law, in which the mathematical expectation of signal is equal to the difference in the mean numbers of charge fluxes, generated by the signal + noise additive mixture and the reading signal, and the variance is the sum of the variances of the aforementioned fluxes [6]. With allowance for this approximation, expression (4) can be rewritten in the form

$$\ln\Lambda = -\frac{1}{2}\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}} - \bar{N}_{\mathrm{r}}) + \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}\right] + \frac{1}{2}(\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}) - \frac{\left[\bar{N} - \bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}} - \bar{N}_{\mathrm{r}}) + \bar{N}_{\mathrm{r}}\right]^2}{2\left[\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}}) + \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}\right]} + \frac{\bar{N} - \bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{n}} - \bar{N}_{\mathrm{r}}) + \bar{N}_{\mathrm{r}}}{2(\bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}})}. \tag{5}$$

An analysis of expression (5) suggests that only two last terms in it depend on the value of the useful signal $\bar{N}$. Having denoted the sum of the terms of expression (5) that are independent of the accepted useful signal as C_1 and performing some evident transformations, we obtain

$$\ln\Lambda = C_1 + \frac{\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{s}} - \bar{N}_{\mathrm{r}})}{\bar{N}_{\mathrm{s}}\beta(\bar{N}_{\mathrm{s}} - \bar{N}_{\mathrm{r}}) + \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}}\left(\bar{N} - \bar{N}_{\mathrm{n}} + \bar{N}_{\mathrm{r}}\right). \tag{6}$$

Further transformations of the likelihood ratio logarithm (6) at the output of optimal detector will be performed taking into account that one the significant factors affecting the validity of the conditions $\beta(\bar{N}_{\rm n}) \to 1$ and $\bar{N}_{\rm r} \to 1$ is the accumulation time of the signal + noise additive mixture, $T_{\rm A}$, which, in turn, is set based on the conditions for forming an object image of specified quality. With allowance for the aforesaid, we will divide the entire accumulation interval of the signal + noise additive mixture, $T_{\rm A}$, into M subintervals and take into account that the mean number of accumulated charges per photodetector element in the vicinity of the upper boundary of the photodetector dynamic range, can be defined as $\bar{N}_{\rm n} + \bar{N}_{\rm s} - \bar{N}_{\rm r}$; i.e.,

$$\bar{N} = \bar{N}_{\rm s} + \bar{N}_{\rm n} - \bar{N}_{\rm r} = \sum_{i=1}^{M} \Big[n_{{\rm s}_i} \beta(n_{{\rm n}_i} - n_{{\rm r}_i}) + n_{{\rm n}_i} - n_{{\rm r}_i} \Big]. \tag{7}$$

With regard to formula (7), the final expression for the likelihood ratio logarithm can be written as

$$\begin{aligned} \ln \Lambda &= C_1 + C_2 \left[\sum_1^M \Big\{ \Big[n_{{\rm s}_i} \beta(n_{{\rm n}_i} - n_{{\rm r}_i}) + n_{{\rm n}_i} \Big] - n_{{\rm r}_i} \Big\} - \bar{N}_{\rm n} + \bar{N}_{\rm r} \right] \\ &= C_1 + C_2 \sum_1^M \Big[n_{{\rm s}_i} \beta(n_{{\rm n}_i} - n_{{\rm r}_i}) + n_{{\rm n}_i} - n_{{\rm r}_i} \Big] - C_2(\bar{N}_{\rm n} - \bar{N}_{\rm r}) \\ &= C_3 + C_2 \sum_1^M \Big[n_{{\rm s}_i} \beta(n_{{\rm n}_i} - n_{{\rm r}_i}) + n_{{\rm n}_i} - n_{{\rm r}_i} \Big]. \end{aligned} \tag{8}$$

Here $n_{{\rm s}_i} = \xi_{{\rm s}_i} t_i \beta(n_{{\rm n}_i})$ is the mean number of carriers generated by useful signal in the ith accumulation interval, recalculated to the photodetector input; $n_{{\rm n}_i} = \xi_{{\rm n}_i} t_i$ is the mean number of charge carriers generated by the additive noise (background) in the ith accumulation interval, recalculated to the photodetector input; $n_{{\rm r}_i} = \xi_{{\rm r}_i} t_i$ is the mean number of carriers of reading charges arriving at the photodetector during the ith interval; $\xi_{{\rm s}_i}$, $\xi_{{\rm n}_i}$, and $\xi_{{\rm r}_i}$ are the intensities of, respectively, signal, noise, and reading flux carriers; and C_1, C_2, and C_3 are constants determined by the completeness of information about the signal and noise values and the photodetector dynamic range:

$$\begin{aligned} C_1 &= -\frac{1}{2} \ln \Big[\bar{N}_{\rm s} \beta(\bar{N}_{\rm n} - \bar{N}_{\rm r}) + \bar{N}_{\rm n} + \bar{N}_{\rm r} \Big] + \frac{1}{2}(\bar{N}_{\rm n} + \bar{N}_{\rm r}), \\ C_2 &= \frac{\bar{N}_{\rm s} \beta(\bar{N}_{\rm n} - \bar{N}_{\rm r})}{\bar{N}_{\rm s} \beta(\bar{N}_{\rm n} - \bar{N}_{\rm r}) + \bar{N}_{\rm n} + \bar{N}_{\rm r}}, \\ C_3 &= C_1 - C_2(\bar{N}_{\rm n} - \bar{N}_{\rm r}). \end{aligned} \tag{9}$$

Relation (8) is a mathematical formalization of the algorithm of optimal signal processing, which implies the following operations:

(i) subtraction (simultaneous with charge accumulation in the photodetector) of excess charges that are generated by additive noise and lead to limitation of photodetector dynamic range;

(ii) multiplication of the result by a weighting coefficient, which depends on a priori known (or measured using additional tools) signal and noise values and consideration of the subtracted value of noise charges;

(iii) comparison of the result obtained with the threshold value.

Let us analyze the possibility of implementing additive noise subtraction. Note that this operation is present as an argument of function β (random in the general case), which describes the transfer coefficient of photodetector with allowance for the finite capacitance of its resolution element. This fact leads to the following fundamental conclusion: the subtraction of additive noise must be performed either on the optical carrier (pre-detector subtraction) or directly in the photodetector before the final light conversion into electric signal (intradetector subtraction). An analysis of expression (8) suggests also that the procedure of subtracting charges generated by the additive noise component of the received signal + noise mixture can be controlled by changing (on real-time scale) the intensity of the additional carrier flux and the duration of its effect. When subtracting the additive noise, one must also take into account the real relations between the noise illuminances in each resolution element of the recorded image and the upper boundary of the photodetector dynamic range, as well as the desired quality of the image formed or object transform.

The pre-detector subtraction of additive noise is a fairly complex technical problem. Currently, it can be implemented using, for example, coherent interferometric methods [6]. Intradetector subtraction can also be performed, in particular, due to the partial recombination of charges generated in the pho-

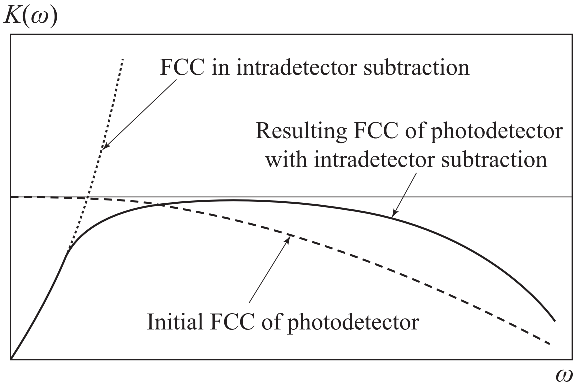

Fig. 1. The FCC of photodetector without intradetector subtraction, the FCC of subtraction, and the resulting FCC of photodetector with intradetector subtraction.

todetector semiconductor layer under recorded optical field and additional charge carriers of opposite sign, forcibly injected into the semiconductor. Depending on the photodetector type, additional carriers can be supplied by photodetector electrodes, external electromagnetic field, electron guns, etc. In our previous studies [1, 4], we reported some circuit designs illustrating the possibility of technical implementation of intradetector subtraction of additive noise by injecting additional charge carriers over different technological time intervals, characteristic of video photodetectors (return trace ranges for frame and line scans, ranges of multiframe period of signal accumulation, etc.). On the whole, the results obtained suggest that real-time subtraction of the excess accumulated charge generated under external additive noise allows one to reduce significantly the effect of the limitation of photodetector dynamic range on the quality of object image formed.

In addition to the aforementioned possibilities on reducing the effect of additive noises, intradetector subtraction can be used to solve a number of other important problems related to primary processing of noisy and distorted images. Figure 1 [4, 9, 10] presents qualitative dependences illustrating the frequency-contrast characteristic (FCC) of a photodetector without intradetector subtraction, the FCC of subtraction, and the resulting FCC of the photodetector. An analysis of these curves shows that, along with the possibility of forming a dip (with a controlled width and depth) in the photodetector FCC in the range of lower spatial frequencies of the recorded image (in which the energy of distributed additive noise is concentrated), shows also that the FCC can be raised in the range of upper spatial frequencies. In principle, simultaneous implementation of these possibilities allows one to perform adaptive correction of the photodetector resolution and increase the quality of recorded images of objects observed both as a result of weakening the effect of the accumulated charge spread (caused by intense noisy illumination) and due to the finite size of photodetector resolution elements [9, 10].

To conclude, we should note that an important (for instrumental realization) advantage of the proposed approach, which allows one to improve the quality of images recorded, is the provision (without changing the photodetector design) of adaptive expansion of the dynamic range and improved contrast sensitivity and resolution of photodetector [7].

3. EXPERIMENTAL VERIFICATION OF THE REALIZABILITY AND EFFICIENCY OF METHODS FOR ADDITIVE-NOISE SUBTRACTION

The possibility of subtracting additive noise in a video photodetector was investigated on an experimental setup, the block diagram of which is shown in Fig. 2. The experimental study included the following stages:

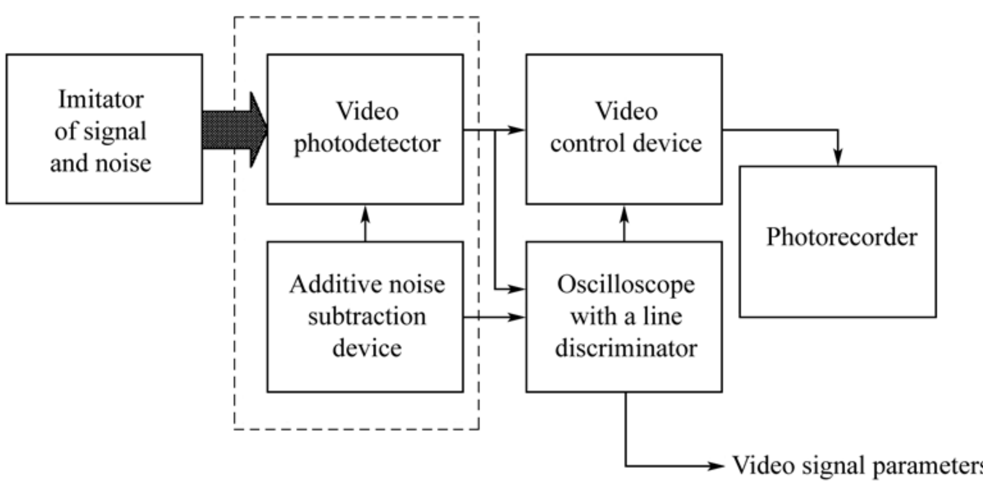

Fig. 2. Block diagram of the experimental setup.

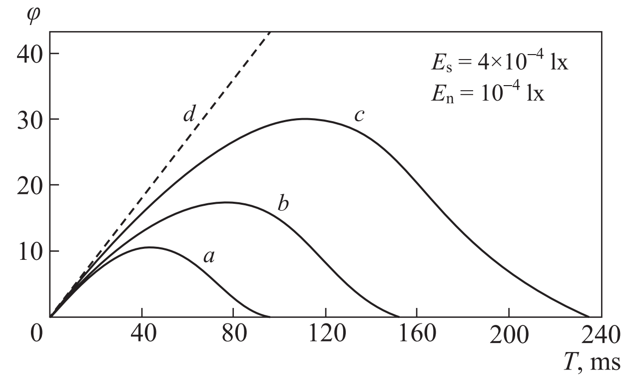

Fig. 3. Experimental and calculated dependences of the output signal-to-noise ratio on the signal accumulation time: (a) without intradetector compensation for additive noise (experiment), (b, c) at different degrees of intradetector subtraction of noise (experiment), and (d) without dynamic range limitation (calculation).

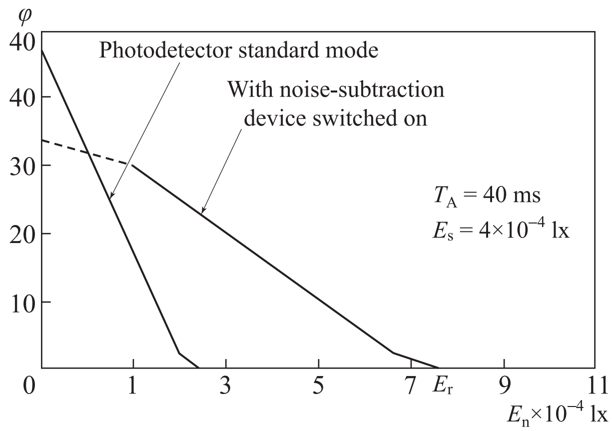

Fig. 4. Experimental dependences of the output signal-to-noise ratio on the additive-noise brightness for photodetector operation in the standard mode and for intradetector subtraction of noise during line-scan return trace.

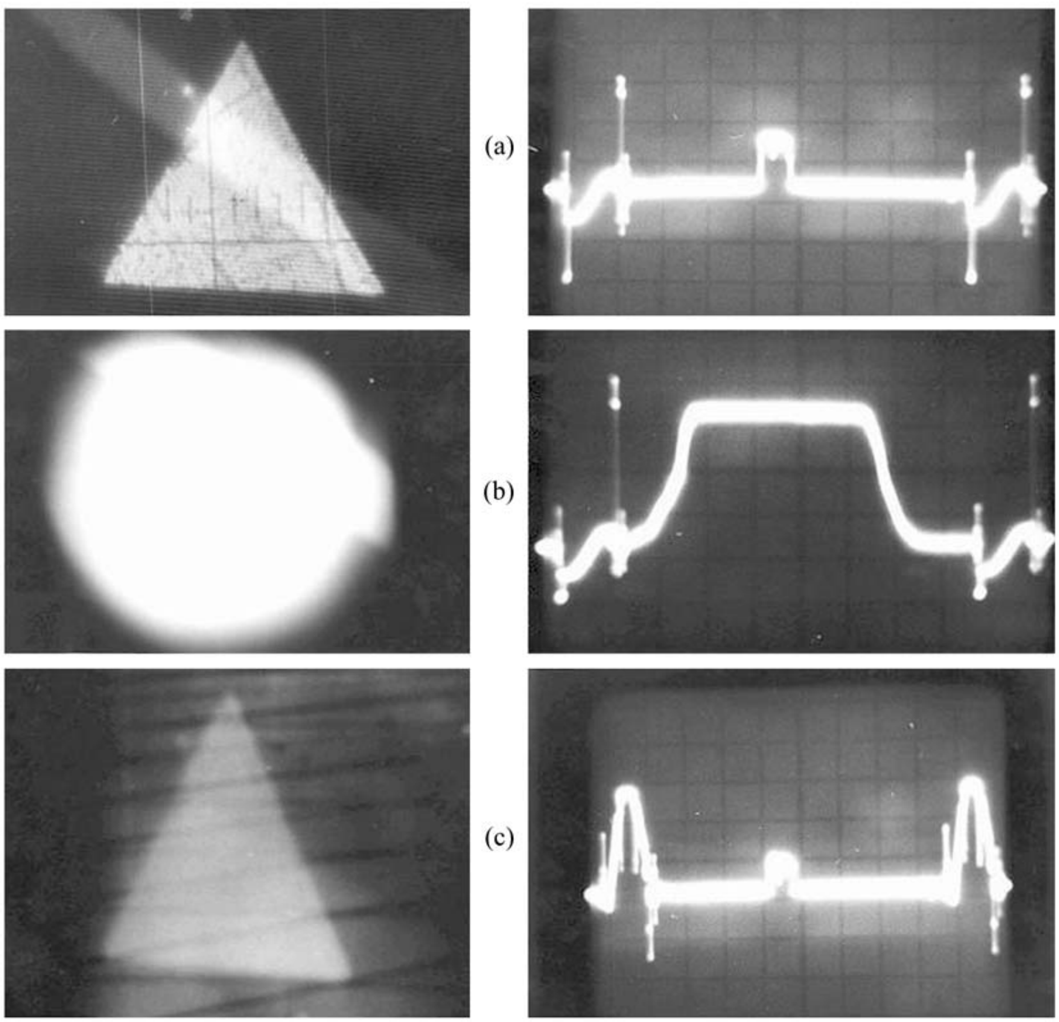

Fig. 5. Operation of the device for intradetector additive-noise subtraction during object image formation by a video photodetector: (a) without additive noise, with subtraction device switched off; (b) photodetector saturation under additive noise, with subtraction device switched off; and (c) the result of switching on the subtraction device at the additive-noise level corresponding to panel (b).

(i) measurement of the parameters of object image signal in the absence of external additive noise;

(ii) measurement of the parameters of object image signal under exposure of photodetector to external additive noise, the illuminance of which does not exceed the upper boundary of the photodetector dynamic range;

(iii) measurement of the parameters of object image signal at an illuminance of external additive noise exceeding the upper boundary of the photodetector dynamic range, with subtraction switched off;

(iv) measurement of the parameters of object image signal at an illuminance of external additive noise exceeding the upper boundary of the photodetector dynamic range, with subtraction switched on.

In each of these stages we measured the illuminances of the signal and noise components of light, observed the recorded video on the monitor of video control device, and calculated the signal-to-noise ratio φ at the output.

The experimental results are presented in Figs. 3–5.

Figure 3 shows calculated and experimental dependences of the output signal-to-noise ratio on the signal accumulation time, with additive noise subtracted during multiframe accumulation interval. Curves a, b, and c were obtained experimentally in the standard-operation mode of photodetector without subtracting additive noise (curve a) and at different subtraction levels (curves b and c). Figure 3 shows also a calculated dependence of the output signal-to-noise ratio on the accumulation time without dynamic range limitation (curve d).

Figure 4 shows experimental dependences of the output signal-to-noise ratio on the additive noise brightness for a photodetector operating in the standard mode and for intradetector subtraction of noise during return trace of photodetector line scan.

Figure 5 presents photographs of monitors of the video control device and oscilloscope, which demonstrate the operation of additive-noise subtraction device in the mode of line-scan return trace of photodetector: (a) without additive noise, with a switched-off subtraction device; (b) at an additive-noise level exceeding the photodetector dynamic range, with the subtraction device switched off; and (c) at an additive-noise level corresponding to Fig. 5(b), with the subtraction device switched on. On the whole, the experimental analysis showed the following: (i) the fundamental possibility of implementing intradetector subtraction of additive noise, (ii) the possibility of technical implementation of intradetector subtraction methods by forming additional subtracting fluxes in technological operation modes of video photodetectors; (iii) the possibility of significant expansion (by a factor of more than three) of the video photodetector dynamic range, which potentially improves the characteristics of systems for detecting and measuring image parameters under additive-noise conditions.

4. CONCLUSIONS

Our study was aimed at optimizing noisy-image processing under conditions of intense additive noise and limited photodetector dynamic range. Based on the optimal signal processing algorithm developed by us, the possibility and expediency of improving the quality of recorded images by subtracting additive noise directly in the photodetector was substantiated.

It was also theoretically substantiated and experimentally confirmed that additive noise can be subtracted in a video photodetector due to the forced recombination of charge carriers generated under noisy conditions. The advantage of the proposed approach is that it allows one to expand the photodetector dynamic range (without changing the photodetector design) and increase the contrast sensitivity and resolution, which potentially improves the quality of recorded images.

The results of our study can be used to solve a variety of scientific and applied problems, which imply observation of different objects and measurement of their parameters in the presence of intense additive noise.

REFERENCES

1. V.M. Nikitin, V.N. Fomin, A.I. Nikolaev, and I.L. Borisenkov, *Adaptive Noise Protection in Optoelectronic Information Systems* (Izd-vo BelGU, Belgorod, 2008) [in Russian].
2. V.N. Fomin, V.M. Nikitin, and E.G. Kolomiytsev, "Detection-Measuring Optical Signals in Noisy Environments with a Limited Dynamic Range of the Photodetector," Russ. Phys. J. **53**(12-2), 258 (2010).
3. J.W. Goodman, *Statistical Optics* (Wiley, N.Y., 1985).
4. V.N. Fomin, V.M. Nikitin, and E.G. Kolomiytsev, *Optoelectronic Astrophysical Observations under Noisy Conditions* (Izd-vo MGU, Moscow, 2012) [in Russian].
5. M.S. Malashin, R.P. Kaminskii, and Yu.B. Borisov, *Fundamentals of Designing Laser Radar Systems* (Vysshaya Shkola, Moscow, 1983) [in Russian].

6. V.M. Nikitin, S.G. Garanin, and V.N. Fomin, *Adaptive Noise Protection of Optoelectronic Sensors (for Control and Navigation Systems)* (Izd-vo MGU, Moscow, 2011) [in Russian].

7. V.N. Fomin and V.M. Nikitin, "Algorithms and Methods for Increasing the Contrast Sensitivity of Video Observation Systems," in *Proceedings of the Scientific and Technical Conference Devoted to the 50th Anniversary of the Moscow Institute of Physics and Technology* (Dolgoprudnyi, 1996), p. 73 [in Russian].

8. A.V. Helvas, V.M. Nikitin, and V.N. Fomin, "Charge Spreading Control and Resolving Power Adaptive Correction in Multichannel Laser Measuring Systems," in *International Conference on Fibre Optics & Photonics "PHOTONICS-96"* (Madras, Indian Institute of Technology, 1996), p. 36.

9. R.V. Pavlovich and V.N. Fomin, "Resolving Power Adaptive Correction in Multichannel Laser Measuring Systems," Proc. SPIE. **2249**, 108 (1994).

10. R.V. Pavlovich and V.N. Fomin, "Resolving Power Adaptive Correction in Multichannel Laser Measuring Systems," Proc. SPIE. **2271**, 206 (1994).