Ivan PRUDYUS, Volodymyr SHKLIARSKYI, Borys HUDZ, Andriy REHUSH
LVIV POLYTECHNIC NATIONAL UNIVERSITY, INSTITUTE OF TELECOMMUNICATIONS, RADIOELECTRONICS AND ELECTRONIC ENGINEERING
12 Stepan Bandera St., 79000 Lviv, Ukraine

Signal-to-noise ratio improvement in scanning television optical microscope

Abstract

Scanning television optical microscope is designed to investigate microscopic objects, larger than 0.1 micrometers. To illuminate microobject with this microscope there is used a high resolution cathode ray tube. Low illumination of the tested microobject lets to explore living microorganisms in real time. The current microscopic image has low contrast. To increase image contrast it is necessary to increase microscope sensitivity. The main sources of noise in scanning television optical microscope are: 1) composite video shaper; 2) photomultiplier tube; and 3) scanning cathode ray tube. Detailed analysis of noise sources in video signal of the microscope is presented in the paper. Equations describing the sources are given. Dependencies are plotted and discussed.

Keywords: scanning television optical microscope, cathode ray tube, noise, photomultiplier tube.

1. Introduction

Scanning television optical microscope is designed to investigate microscopic objects, larger than 0.1 micrometer. High resolution cathode ray tube is used to illuminate microobject with this microscope. On the screen of the tube a scanning raster is formed, which corresponds to 5000×5000 decomposition elements of image. Afterglow time of the scanning raster element is very small. This time does not exceeds the moving time of the scanning beam to the next addressed point. Low illumination of the tested microobject lets to explore living microorganisms in real time. The current microscopic image has low contrast. To increase image contrast it is necessary to increase microscope sensitivity. Sensitivity is primarily determined by the signal-to-noise ratio. It determines the ability of a microscope to operate at low illumination of a tested object. As any television system, apart from useful signal a scanning microscope amplifies a noise. If this signal is fed on the television monitor, the noises reveal themselves in the form of light and dark spots, covering an entire screen. Noises get more noticeable on gray and dark areas of the image and weaker on light area, degrading image quality. In terms of noise, image quality is convenient to characterize by the Ψ ratio. It consists of voltage or current pulses randomly distributed in time and magnitude [1]. The Eq. 1 stands:

$$\psi = I_S \Big/ \sqrt{\overline{I}_N^2} \quad \text{or} \quad \psi = U_S \Big/ \sqrt{\overline{U}_N^2} \, . \tag{1}$$

The main sources of noise in scanning television optical microscope are: 1) composite video shaper; 2) photomultiplier tube; and 3) scanning cathode ray tube.

2. Noise component analysis of signal

To analyze the impact of noise and the necessary requirements concerning the composite video signal shaping channel, a block diagram of microscope shown in Fig. 1 there is used. It includes: scanning cathode ray tube (CRT), first optical channel (OC1), test object (TO), second optical channel (OC2), photomultiplier tube (PMT) and composite video signal shaper (SS).

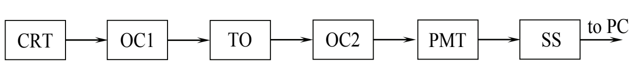

Fig. 1. Block-diagram of video signal shaping in microscope

The first optical channel projects luminous raster on the tested object. The second optical channel collects diffused light from the tested object while microscope is operating in a light-reflecting mode, or collects the light transmitted through the tested object, while microscope is operating in a transillumination mode. The collected light is projected onto the photosensitive target of photomultiplier tube. Photomultiplier tube converts the light signal into electrical one. Composite video signal shaper amplifies signal to a normalized value and mixes it with sync and blanking pulses.

To analysis performing the composite video signal shaper can be represented as an active linear four-pole, which can be described by a differential noise factor (N_{SS}) [1]. Differential noise factor shows how many times the ratio of signal power to noise power for infinitely small bandwidth (dF) gets reduced when passing through the four-pole:

$$N_{SS}(F) = 1 + \frac{S_{NSS}(F)}{S_{NPMT}(F)}, \tag{2}$$

where: $N_{SS}(F)$ – noise factor of composite video signal shaper; $S_{NSS}(F)$ – spectral density of the video shaper signal power with a continuous spectrum; $S_{NPMT}(F)$ – spectral density of the photomultiplier signal power with a continuous spectrum.

If a composite video signal shaper consists of n linear stages, then

$$N_{SS}(F) = N_{1SS}(F) + \frac{N_{2SS}(F)-1}{G_{1SS}(F)} + \ldots + \frac{N_{nSS}(F)-1}{G_{1SS}(F)\ G_{2SS}(F)\cdot\ldots\cdot G_{(n-1)SS}(F)} \tag{3}$$

where: $N_{nSS}(F)$ – noise factor of n-th stage; $G_{(n-1)SS}(F)$ – gain of n-th stage.

Assume that the intrinsic noise from the composite video signal shaper is a white noise. Then its differential and integral (average) noise factors are numerically equal [1], [2]. With the known value of N_{SS} noise factor one can determine a signal-to-noise ratio at the shaper input, which is necessary to provide for a given image quality:

$$\Psi_{InSS} = \Psi_{OutSS} \cdot N_{SS}, \tag{4}$$

where: Ψ_{OutSS} – predetermined signal-to-noise ratio at the composite video signal shaper output.

We define a minimum luminance from the cathode ray tube to produce a desired Ψ_{InSS} value, under condition at that cathode ray tube, photomultiplier tube and photomultiplier load resistance (R_L) make no noises. If luminous flux (F_{TO}) is incident on a photocathode surface from the microobject element, then the current, flowing at the output of photomultiplier tube, will be:

$$I_{PMT} = \varepsilon \cdot F_{TO} \cdot P_{OC2} \cdot \Omega_{OC2} = \frac{\varepsilon \cdot F_{TO} \cdot P_{OC2} \cdot S_{OC2}}{L_{OC2}^2} \, . \tag{5}$$

where: ε – photomultiplier anode sensitivity; P_{OC2}– transmission coefficient of condenser lens in the second optical channel; Ω_{OC2} – solid angle within which the luminous flux from the object reaches the condenser lens; S_{OC2}– entrance pupil area of condenser lens; L_{OC2} – distance from the test object to the condenser lens.

Signal-to-noise ratio at the output of photomultiplier taking into consideration only the intrinsic noise of the signal shaper can be defined as [3], [4]:

$$\psi_{InSS} = \frac{\varepsilon \cdot F_{TO} \cdot P_{OC2} \cdot S_{OC2} \cdot \sqrt{R_L}}{L_{OC2}^2 \cdot \sqrt{4k \cdot T \cdot \Delta F}}. \quad (6)$$

where: R_L – load impedance of photomultiplier; k – Boltzmann constant; T – temperature, K; ΔF – video bandwidth.

Luminous flux from the test object to provide a specified signal-to-noise ratio at the output of photomultiplier tube, which further provides the necessary image quality on the screen, is:

$$F_{TO} = \frac{\psi_{InSS} \cdot L_{OC2}^2 \cdot \sqrt{4k \cdot T \cdot \Delta F}}{\varepsilon \cdot P_{OC2} \cdot S_{OC2} \cdot \sqrt{R_L}}. \quad (7)$$

On the other hand, the luminous flux from test object depends on the raster element luminance (B_{CRT}) of scanning cathode ray tube, area of this element (S_{CRT}), optical transmission coefficient (P_{OC1}) of the microscopic lens which is disposed in the first optical channel and the solid angle (Ω_{OC1}) in which light from the cathode ray tube passes to the test object through the lens:

$$F_{TO} = B_{CRT} \cdot S_{CRT} \cdot P_{OC1} \cdot \Omega_{OC1} = \frac{B_{CRT} \cdot S_{CRT} \cdot S_{OC1} \cdot P_{OC1}}{L_{OC1}^2}. \quad (8)$$

where: S_{OC1} – entrance pupil area of microscope lens; L_{OC1} – length from the plane of scanning tube screen to the microscope objective.

Minimum value of spot luminance for scanning cathode ray tube, which is necessary to ensure a specified signal-to-noise ratio at the input of the signal shaper [4], [5], is:

$$B_{CRT} = \frac{\psi_{InSS} \cdot L_{OC1}^2 \cdot L_{OC2}^2}{\varepsilon \cdot P_{OC1} \cdot P_{OC2} \cdot S_{OC1} \cdot S_{OC2} \cdot S_{CRT}} \cdot \sqrt{\frac{4k \cdot T \cdot \Delta F}{R_L}}. \quad (9)$$

Consider the effect of cathode ray tube noise on the image quality from test object [6]:

$$\overline{U}_{NCRT}^2 = \frac{J_0^2 \cdot A \cdot R_L^2 \cdot M^2 \cdot P_{OC1} \cdot K^2}{(2\pi)^2} \iint_{-\infty}^{\infty} e^{-r^2 \cdot \left(\omega_x{}^2 + \omega_y{}^2\right)} \mathrm{d}\omega_x \mathrm{d}\omega_y, \quad (10)$$

where: $\overline{U}_{NCRT}^2$ – noise dispersion at the output of photomultiplier, generated by cathode ray tube, when photomultiplier noise absent; J_0 – current density in the center of electron beam; A – coefficient, taking into account the change in light output of luminophore on the tube screen field (at small angles of deviation close to 1); M – photomultiplier gain; K – transmission coefficient of optical system; r – beam radius; ω_x, ω_y – circular spatial frequencies.

Another source of noise is the photomultiplier tube. Unlike photovoltaic cells, their noises are determined only by the intrinsic fluctuations (random oscillations) of photoelectron and thermionic photocathode emissions; in the photomultipliers these processes are made complicated by secondary electron emission, which is also characterized by the statistical fluctuations of the secondary emission coefficient (σ).

Total dispersion of the anode current ($\overline{I}_{NPMT}^2$), which determines the intrinsic photomultiplier noise is equal to the sum of two independent dispersion components. The first component is the dispersion of amplified current fluctuations from the photocathode. The second component is the dispersion of anode current fluctuations, associated with the secondary emission. That is:

$$\overline{I}_{NPMT}^2 = \overline{I}_{NC}^2 \cdot M^2 + \cdot \overline{I}_{NC}^2 \cdot M^2 \cdot \beta_m, \quad (11)$$

where: $\overline{I}_{NC}^2$ – fluctuations of photocathode emission current; M – photomultiplier gain ($M=\sigma^m$); β_m – value of gain quadratic variation, which is determined according to the expression:

$$\beta_m = \frac{\sigma^m - 1}{\sigma^m (\sigma - 1)}, \quad (12)$$

where: m – number of gain stages in photomultiplier.

Since σ^m>>1, then we can write

$$\beta_m = \frac{1}{\sigma - 1}. \quad (13)$$

The value of $\overline{I}_{NC}^2$ can be written as

$$\overline{I}_{NC}^2 = 2\mathrm{e} \cdot I_0 \cdot \Delta F, \quad (14)$$

where: I_0 – photomultiplier dark current; ΔF – video bandwidth; e – electron charge.

Total current dispersion at the output of photomultiplier will be:

$$\overline{I}_{NPMT}^2 = 2\mathrm{e} \cdot I_0 \cdot \Delta F \cdot \frac{\sigma^{2m+1}}{\sigma - 1}. \quad (15)$$

The amplified signal at the output of photomultiplier is as follows:

$$I_{PMT} = I_0 \cdot M = I_0 \cdot \sigma^m. \quad (16)$$

Mean square deviation of current at the photomultiplier output is:

$$\overline{I}_{NPMT}^2 = 2\mathrm{e} \cdot \frac{I_{PMT}}{\sigma^m} \cdot \Delta F \cdot \frac{\sigma^{2m+1}}{\sigma - 1}. \quad (17)$$

The effect of load resistor noise in photomultiplier to the image quality can be defined using the known expression:

$$\overline{U}_{NR_L}^2 = 4k \cdot T \cdot R_N \cdot \Delta F. \quad (18)$$

The total mean square noise at the output of the photomultiplier tube with including the cathode ray tube noise is determined as:

$$\overline{I}_{\mathrm{PMT}\ \Sigma}^2 = \overline{I}_{NPMT}^2 + \frac{\overline{U}_{NR_L}^2 + \overline{U}_{NCRT}^2}{R_L^2}. \quad (19)$$

The analysis showed that the cathode ray tube noise in comparison with the noise of the photomultiplier can be ignored, since

$$\overline{I}_{\mathrm{PMT}\ \Sigma}^2 = \overline{I}_{NPMT}^2 + \frac{\overline{U}_{NR_L}^2}{R_L^2} = 2\mathrm{e} \cdot \frac{I_{PMT}}{\sigma^m} \cdot \Delta F \cdot \frac{\sigma^{2m+1}}{\sigma - 1} + \frac{4k \cdot T \cdot \Delta F}{R_L}, \quad (20)$$

and the signal-to-noise ratio at the output of photomultiplier tube has the following form:

$$\psi_{PMT} = \frac{I_{PMT} \cdot \sqrt{R_L \cdot (\sigma - 1)}}{\sqrt{2e \cdot I_{PMT} \cdot \Delta F \cdot R_L \cdot \sigma^{m+1} + 4k \cdot T \cdot \Delta F \cdot (\sigma - 1)}} \quad (21)$$

To provide a specified image quality of the test object, a $\Psi_{PMT} > \Psi_{InSS}$ condition must be fulfilled.

Quantitative evaluation of terms under the square root in the denominator shows that the biggest impact on the value of signal-to-noise ratio is the secondary emission coefficient of the photomultiplier tube. Fig. 2 shows a plot of $\Psi_{PMT} = f(\sigma)$ at load resistance R_L = 10 MΩ, current I_{PMT} = 0.1 mA and video signal bandwidth ΔF = 10 MHz.

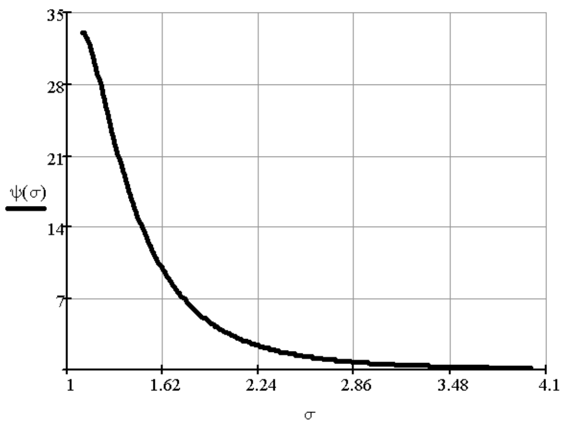

Fig. 2. Dependence of signal-to-noise ratio from the secondary emission coefficient

The plot in Fig. 2 shows, that to increase the signal-to-noise ratio it is necessary to reduce the secondary emission coefficient. This will reduce the photomultiplier and microscopy gain. With decrease in doubled of the secondary emission coefficient (from σ = 3 to σ = 1.5), the signal-to-noise ratio increases from 1 to 14, i.e. 14 times. It should be noted that the photomultiplier gain decreases by 2^{10} = 1024 times. When noise factor N_{SS} = 1.2 and Ψ_{OutSS} = 25 (medium image quality) of the signal shaper, then Ψ_{InSS} = 30. To ensure the $\Psi_{PMT} > \Psi_{InSS}$, according to Fig. 2, the value of the secondary emission coefficient should not exceed 1.2.

Fig. 3 shows the dependence of the signal-to-noise ratio at the output of photomultiplier tube on the secondary emission coefficient at different video bandwidths (ΔF_1 = 1 MHz, ΔF_2= 6,5 MHz, ΔF_3= 10 MHz).

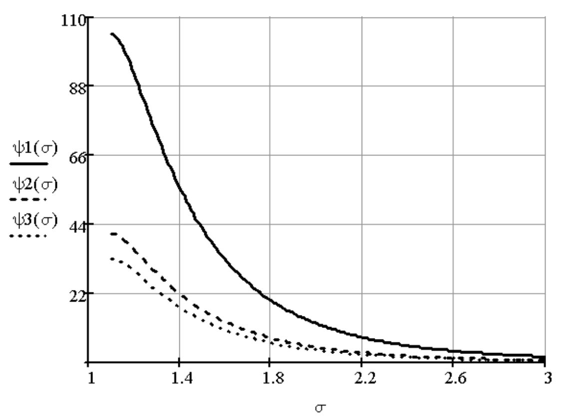

Fig. 3. Dependence of signal-to-noise ratio on the secondary emission coefficient at the different bandwidths

From these dependencies one can see, that with decreasing bandwidth the signal-to-noise ratio is improved. In this case, the change rate of signal-to-noise ratio is increased at a low frequencies range. In the case of reducing the bandwidth from 10 MHz to 1 MHz signal-to-noise ratio is increased from Ψ_{PMT} = 16 to Ψ_{PMT} = 56, that is 3.5 times (when the secondary emission coefficient σ = 1.4).

Fig. 4 shows the dependence of the signal-to-noise ratio at the output of the photomultiplier load resistance.

From the dependence (Fig. 4) we see, that the signal-to-noise ratio decreases sharply for loads of resistors less than 200 kΩ. By increasing the resistance it is almost independent. On the other hand from the Eq. (9) one can see the following: the larger load resistance of photomultiplier, the lower luminance of the scanning spot on the tube screen can have. Therefore it is better to ensure the biggest possible load resistance from the condition of the required bandwidth provided.

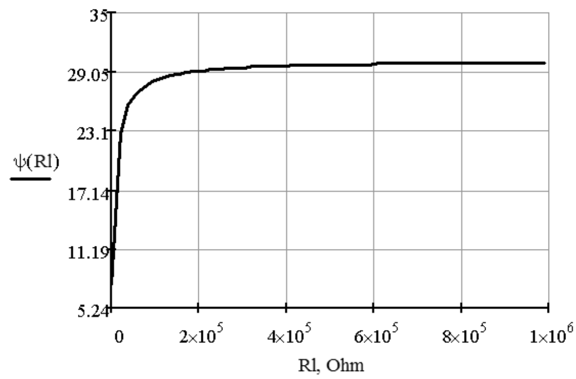

Fig. 4. Dependence of the signal-to-noise ratio at the photomultiplier output on the load resistance

Dependence of the signal-to-noise ratio on the photomultiplier current is shown in Fig. 5.

The plot shows, that to increase the signal-to-noise ratio it is necessary to increase the photomultiplier current, requiring an increase of the supply voltage. However, this leads to an increase in the secondary emission coefficient, which consequently worsens the signal-to-noise ratio.

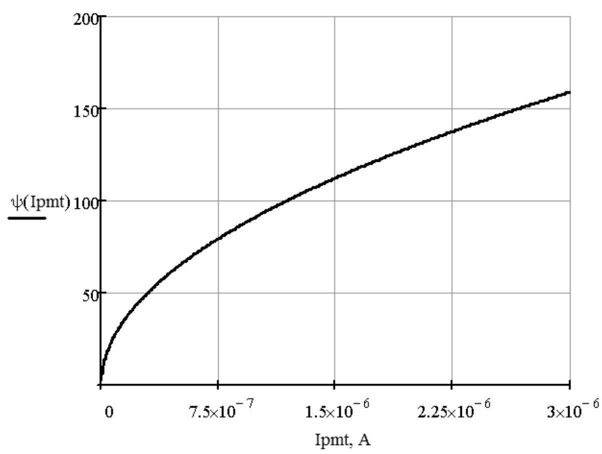

Fig. 5. Dependence of the signal-to-noise ratio on the photomultiplier current

When the parameters of the microscope photomultiplier sensitivity in accordance with Eq. (9) are known, we can find a necessary luminance of the cathode ray tube screen, as well as the dependence of the B_{CRT} on the load resistance.

When using photomultiplier anode sensitivity of ε = 30 A/lm, according to Eq. (9) the minimum necessary luminance of scanning cathode ray tube at Ψ = 25; N_{SS} = 1.2; L_{OC1} = 0.5 m; L_{OC2} = 0.01 m; P_{OC1} = 0.8; P_{OC2} = 0.8; S_{OC1}=$2\cdot10^{-5}$ m^2 (entrance pupil diameter of microscope objective 5 mm); S_{OC2} = $8\cdot10^{-5}$ m^2 (entrance pupil diameter of condenser 10 mm); S_{CRT} = $4\cdot10^{-10}$ m^2 (area of one element at the raster size 40×40 mm^2 on the screen of scanning tube and resolution 2000×2000 elements); ΔF = 10 MHz; k = 1.37 10^{-23} J/K; T = 290 K; R_L = 10 MΩ, will be 7694 cd/m^2.

Special projection cathode ray tubes, usually provide such luminance.

The dependence of the required luminance spot of scanning tube for the specified signal-to-noise ratio on the load resistance is shown in Fig. 6.

To ensure high quality imaging there should be selected photomultipliers with higher cathode sensitivity, increasing the load resistor to the extent permitted in terms of bandwidth and by reducing the speed of scanning beam in a scanning tube. Reducing scanning speed leads to a decrease the video bandwidth [6], [7].

This method of determining the minimum necessary luminance of the scanning tube allows easier selection of the photomultipliers to convert light signal into an electrical signal taking into account the cathode ray tube noise, photomultiplier intrinsic noise and photomultiplier photocathode sensitivity. Additionally, one can define the requirements for video shaper noise in terms of providing a given image quality on the monitor screen.

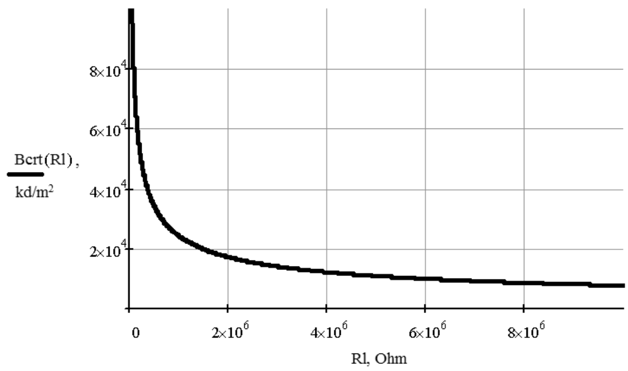

Fig. 6. Luminance dependence of cathode ray tube on the photomultiplier load resistance

3. Conclusions

The analysis performed allows simplifying the selection of operating modes for scanning television optical microscope in terms of increasing its sensitivity. Charts provided in the report allow choosing the optimum load resistance of photomultiplier tube and the necessary bandwidth of composite video signal shaping mode from the point of view of ensuring the required imaging quality of the tested microobject.

4. References

[1] Van der Ziel A.: Noise. Sources, Characterization, Measurement. Prentice-Hall Electrical Engineering Series. Englewood Cliffs, New Jersey, March, 1971.

[2] Hrytskiv Z., Shkliarskyi V.: Determination of the luminance of CRT for scanning optical microscope based on noise. Bulletin of Lviv Polytechnic National University. Radioelectronics and Communication, no 428, 2001, p. 54 - 58 (In Ukrainian).

[3] Hrytskiv Z.: Television–computer scanning optical microscope: foretime, nowadays and the near future. Telecommunication in Modern Satellite, Cable and Broadcasting Services TELSICS’2005: 7-th Int. Conf. Nis, Serbia and Montenegro, September 28-30, 2005, p. 243-252.

[4] Shkliarskyi V.: Television scanning optical microscopy: theory and practice. A monograph, Lviv Polytechnic, 2010, p. 456 (In Ukrainian)

[5] Shkliarskyi V. I.: About the possibility of formation the amplitude-frequency response for photomultiplier amplifier. Bulletin of State. Univ. "Lviv Polytechnic": Theory and design of semiconductors and electronic devices. 1998, no 343, pp. 24-25 (In Ukrainian).

[6] Vaskov O. T., Mamontov G. M., Potashnikov A. K., Tkach S. E.: Scanning devices on high resolution CRT. Publishing House "Nauka", Siberian Branch, Novosibirsk, 1978, pp. 138 (In Russian).

[7] Wilson T.: Theory and Practice of Scanning Optical Microscopy. In T. Wilson, C.J.R. Sheppard – London: Academic Press, 1984. – 213 p.

Received: 21.05.2015 *Paper reviewed* *Accepted: 02.07.2015*

Prof. Ivan PRUDYUS, DSc

Ivan Prudyus was born in Ukraine in 1942. Received the PhD degree in 1980. From 2001 he is Professor of the Radioelectronic Devices and Systems department. From 2004 he is Director of the Institute of Telecommunications, Radioelectronics and Electronic Engineering. In 2005 he received the DSc degree. From 2007 to 2015 he also worked as the Head of the Radioelectronic Devices and Systems department. Basic directions of scientific researches: antennas, antenna systems, multispectral monitoring systems and complexes.

e-mail: iprudyus@polynet.lviv.ua

Prof. Volodymyr SHKLIARSKYI, DSc

Volodymyr Shkliarskyi was born in Ukraine in 1949. In 1991 he received the PhD degree. From 2002 he work as a Head of Research Department of the Radio Systems. Professor of the Department of Radioelectronic Devices and Systems, Institute of Telecommunications, Radioelectronics and Electronic Engineering. From 2015 he is the Head of the Radioelectronic Devices and Systems department. Basic directions of scientific researches: television scanning systems.

e-mail: shkliarskyi@ukr.net

Borys HUDZ

Borys Hudz was born in 1988. Postgraduate of the Radioelectronic Devices and Systems department, Institute of Telecommunications, Radioelectronics and Electronic Engineering. Research interests: television measuring systems.

e-mail: HudzBV@yandex.ru

Andriy REHUSH

Andriy Rehush was born in 1990. Postgraduate of the Department of Radioelectronic Devices and Systems, Institute of Telecommunications, Radioelectronics and Electronic Engineering. Research interests: television measuring systems.

e-mail: breezy90@yandex.ru