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Increasing the Measurement Accuracy of Wide-aperture Photometer Based on Digital Camera

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To reduce the cost and time of testing the lighting characteristics of LED sources, a photometer design based on a fiber-optic focon has been proposed and patented for measuring the spatial distribution of radiation without rotation. The results of studies of the spectral characteristics of the digital cameras with CCD-matrices included in this wide-aperture photometer as a photodetector matrix have been presented in the paper. The spectral characteristics of the matrix photodetectors have been investigated in accordance with the procedure of CIE standardization (ISO/CIE 19476:2014). The deviation of the obtained spectral characteristics from the standard function of the relative spectral luminous efficiency of monochromatic radiation for photopic vision $V(\lambda)$ has determined the measurement error of the photometric body of light devices. It was established that measurement of the spectral characteristics of digital camera matrices only on the "green channel" is not sufficient, since the mismatch between the measurement result and the function of relative spectral luminous efficiency of monochromatic radiation for photopic vision is in the range from 6 % to 22.5 %. Based on the range of color temperatures of the sources of visible radiation, which are mainly used for illumination, the error estimate of the proposed photometer was performed for thirteen LED light sources with typical spectral characteristics that most fully cover the spectrum of light sources on the market in terms of the range of correlated color temperatures T_C: 2700-8400 K. To ensure the specified accuracy of photometers by correcting the spectral responsivity characteristic $S_{rel}(\lambda)$ of digital camera, a correction optical filter with the corresponding characteristics is used. As an optical filter, it is proposed to use a combination of three-color optical filters ZS 8, SZS 24 and ZhZS 18. The spectral transmission characteristics of the optical filter are determined by the combined use of these three glass grades, the thickness of each is selected separately. It is shown that with the use of the developed correction filter, which is a combination of 3 types of glass, it is possible to reduce the error of spectral measurements to 5 %.

Keywords: Photometer, Luminous flux, Spectral responsivity of the receiver, Digital camera.

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1. INTRODUCTION

The body's reaction to light is closely related to electrical, chemical, biological, and psychological processes and is difficult to measure. Therefore, in 1979, when determining the base unit of light, energy and light measurements were connected together. An unambiguous connection was established for monochromatic radiation at the wavelength of maximum sensitivity of the human eye. At the same time, the relative spectral luminous efficiency of monochromatic radiation for photopic vision was standardized. Due to this, the whole set of radiation energy characteristics, which describe both radiation sources and detectors, turned out to be applicable for light measurements. Light measurements were found to be directly related to the reaction of the human body to radiation and were narrowed down to a set of reduced values: illuminance, luminance, luminous intensity and luminous flux. These quantities are expressed through each other by simple formulas using geometric quantities. The initial element in the creation of illuminance is a source, and the final element is a detector. Luminous quantities characterize both of these elements. If the spectral responsivity of an electro-optical detector matches the spectral sensitivity of the human eye, then the detector produces a signal proportional to the luminous flux incident on it, or, in the case of a uniform distribution, proportional to the illuminance. Knowing the illuminance distribution, we can get the spatial distribution of the luminous intensity of the source that generates this illuminance. The main difficulties in these measurements are related to the difficulty of matching the spectral responsivity of a detector with the spectral sensitivity of the human eye, as well as the difficulty of measuring the spatial distribution of radiation, which is traditionally carried out by goniometric installations.

Traditional methods and instruments used for measuring the lighting characteristics have several disadvantages: high cost, considerable time for receiving and processing measurement results. To eliminate them, as well as to automate the process of measuring the lighting characteristics of LED light sources and devices, a photometer was designed [1] based on a fiber-optic focon and photodetector matrix with a correction optical filter (Fig. 1).

The structure of the focon allows to measure the angular distribution of the radiation of the investigated source incident on it without using a rotation device.

The characteristics of modern digital cameras with matrix (CCD) filters make it possible to use them in such a photometer as a photodetector matrix [2].

However, the widespread use of amateur and professional cameras in scientific measurements is difficult for two main reasons [3]: 1) the distortion of

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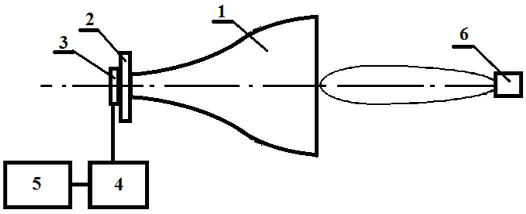

Fig. 1 – Photometer scheme with automated determination of radiation parameters: 1 – fiber-optic focon; 2 – optical filter; 3 – photodetector matrix; 4 – information processing unit; 5 – visualization unit; 6 – radiation source

information about the distribution of intensity in the image processing by built-in software after registration; 2) the absence in open access of data on such characteristics of camera matrices as: radiometric function (dependence of the signal recorded by the receiver on the photometric value), noise and spectral characteristics. Guidelines for measuring, calculating and presenting the characteristics of various digital cameras and the matrices used in them, including the integral spectral response, are defined in the European standard EMVA – 1288 [4]. However, in the EMVA – 1288 standard, the method of measuring the spectral characteristics of individual color channels of color matrix photodetectors is not standardized.

To ensure the specified accuracy of photometers and to evaluate the possibility of their use for measuring the spatial distribution of the radiation intensity in the visible range, it is necessary to investigate the spectral characteristics of the matrix photodetectors. The deviation of the obtained spectral characteristics from the standard function of the relative spectral luminous efficiency of monochromatic radiation for photopic vision $V(\lambda)$ determines the measurement error of the photometric body of light devices.

The aim of the work is to reduce the measurement error of a wide-aperture photometer based on a fiber-optic focon in the case of using modern digital cameras for recording the signal of matrices.

2. STATEMENT OF THE PROBLEM OF RESEARCH

To reduce the measurement error with a wide-angle photometer based on a fiber-optic focon, in case of use of modern matrices of digital cameras to record the signal, it is necessary to solve the following problems:

– based on the analysis of existing methods for evaluating the spectral responsivity characteristics of digital camera matrices, to develop a method for measuring the characteristics of correction filters for these cameras;

– to propose an experimental setup and to perform the measurement of spectral characteristics of the photometer;

– to carry out the processing and analysis of the results;

– to develop recommendations for further enhancement of the photometer.

To assess the possibility of using a digital camera with a matrix filter as a photodetector matrix of a photometer based on a fiber-optic focon, studies of the spectral characteristics of the above cameras were carried out in accordance with the procedure [5].

The relative spectral responsivity, $s_{rel}(\lambda)$, of a photometer shall match the spectral luminous efficiency function for photopic vision $V(\lambda)$ [5]. This match should be verified regularly. A simple verification method is to calibrate a photometer with CIE Standard Illuminant A [6], and then compare the photometer's luminous characteristic caused by an unknown (for example, LED) source with the light response of a reference measuring instrument.

There are various parameters to describe the quality of the spectral match. Most quality indicators are based on absolute comparisons between ideal properties and those being measured.

If the relative spectral distribution of the source $S_z(\lambda)$ and the relative spectral responsivity of the detector are known, the indications of the photometer should be corrected using the spectral mismatch correction factor $F^*(S_z(\lambda))$. If information on the relative spectral distribution of the source is not available, the concept of the mismatch indicator $f_1(S_z(\lambda))$ can be used to estimate photometer characteristics.

To characterize the quality of a photometer with respect to light sources with different spectral distribution, it is important to know the spectral responsivity of the photometer. Spectral measurements should be performed in accordance with the recommendations given in CIE 202:2011 [7].

The responsivity of a photometer is usually defined as the quotient of the detector output by the detector input. In photometry the input radiation is spectrally weighted (normalized) by the spectral luminous efficiency function $V(\lambda)$. The resulting responsivity is called the absolute luminous responsivity, S_v, and is defined as follows:

$$S_v = \left(\int_{\lambda min}^{\lambda max} S_z(\lambda) \cdot s(\lambda) d\lambda \right) \Bigg/ \left(K_{max} \int_{360nm}^{830nm} S_z(\lambda) \cdot V(\lambda) d\lambda \right), \quad (1)$$

where $K_m \cong 683$ lm·W^{-1} (in standard air), $s(\lambda)$ is the spectral responsivity of the photometer, $S_z(\lambda)$ is the relative spectral distribution of the light source being measured.

For photometric measurement using a photometer whose spectral responsivity differs in certain spectral ranges from the prescribed weighting function, incorrect measurement results are obtained. When using the spectrally integrated responsivity function, such differences may compensate each other to some extent when comparing two spectral distributions, e.g. LED light source, let's call it Z, and CIE Standard Illuminant A. To calculate this, the knowledge of the relative spectral responsivity of the photometer, $s_{rel}(\lambda)$, and the relative spectral distribution of the light source Z, $S_z(\lambda)$, is sufficient.

The determination of the function $V(\lambda)$ covers the full photometric spectral range from 360 nm to 830 nm. In practice, measurements at the limits of the spectral range are very complex. To estimate $f_1(S_z(\lambda))$, it is sufficient to perform measurements of the relative spectral responsivity in the wavelength range from 380 nm to 780 nm.

The relative luminous responsivity $a^*(S_z(\lambda))$ can be obtained from the ratio of the luminous responsivity S_z when the detector is illuminated with light source Z to the luminous responsivity S_A when it is illuminated with CIE Standard Illuminant *A*:

$$a*(S_z(\lambda)) = \frac{s_z}{s_A} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} S_z(\lambda)\cdot s_{rel}(\lambda)d\lambda}{\int_{380nm}^{780nm} S_z(\lambda)\cdot V(\lambda)d\lambda} \Bigg/ \frac{\int_{\lambda_{min}}^{\lambda_{max}} S_A(\lambda)\cdot s_{rel}d\lambda}{\int_{380nm}^{780nm} S_A(\lambda)\cdot V(\lambda)d\lambda}, \quad (2)$$

where S_z is the luminous responsivity of the photometer using light source *Z*, S_A is the luminous responsivity of the photometer using CIE Standard Illuminant *A*.

The lower and upper integration limits λ_{min} and λ_{max} refer to the wavelength range where $s_{rel}(\lambda)$ has non-zero values. In our case, they are 380 nm and 780 nm, respectively.

The reciprocal of $a^*(S_z(\lambda))$ is called the spectral mismatch correction factor $F^*(S_z(\lambda))$, which is determined by the formula:

$$F^*(S_z(\lambda)) = (a^*(S_z(\lambda)))^{-1}. \quad (3)$$

If the relative spectral responsivity of the photometer and the relative spectral distribution of the source are known, the measurement shall be corrected according to equation (2). For spectrally narrow light sources (e.g. LEDs), applying a spectral mismatch correction factor is most important.

The quality of the spectral match of the photometer to the $V(\lambda)$ function for a specific light source can be expressed by the specific mismatch:

$$f_1(S_z(\lambda)) = a^*(S_z(\lambda)) - 1 \quad (4)$$

or taking into account 2 it can be presented in the form:

$$f_1(S_z(\lambda)) = \left(\frac{\int_{380}^{780} S_z(\lambda)\cdot s_{rel}(\lambda)d\lambda}{\int_{380}^{780} S_z(\lambda)\cdot V(\lambda)d\lambda}\frac{\int_{380}^{780} S_A(\lambda)\cdot V(\lambda)d\lambda}{\int_{380}^{780} S_A(\lambda)\cdot s_{rel}(\lambda)d\lambda} - 1\right)\cdot 100\% \quad (5)$$

This value shows the difference in the measurement result of the photometer calibrated against CIE Standard Illuminant A when measuring the radiation source with the spectrum $S_z(\lambda)$.

Measurements of the spectral characteristics should be performed in accordance with the recommendations given in [7]. To evaluate the measurement results of the relative spectral responsivity of digital camera matrices in the spectral range from 380 nm to 780 nm, calculations were performed for data with a step of 10 nm.

The block diagram of the installation for measuring the spectral characteristics of the detector matrices of digital cameras is shown in Fig. 2.

3. MEASUREMENT RESULTS OF THE CHARACTERISTICS OF MATRIX RECEIVERS

3.1 Study of Spectral Characteristics

The spectral characteristics of the responsivity of Kodak Z981 digital matrices (USA), ICX285AQ and IMX214 matrices manufactured by Sony (Japan), NC81338L matrix of NIKON D700 (Japan) and Olympus SC50 cameras with Aptina MT9P006STC sensor (USA) were studied. The results of studies of the spectral responsivity of all matrix channels and their resulting characteristics are presented in Fig. 3.

Analysis of the spectral characteristics of the matrices of digital cameras presented in Fig. 3 showed that the green channel of matrices is the most informative one to achieve the goal of research.

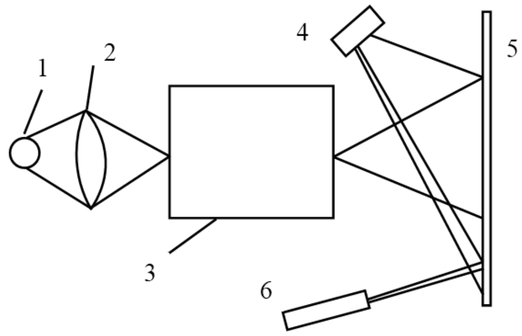

Fig. 2 – Installation scheme for measuring the spectral characteristics of digital cameras: 1 – reference radiation source, 2 – lens, 3 – monochromator, 4 – digital camera, 5 – white matte screen, 6 – radiation source for additional screen illumination

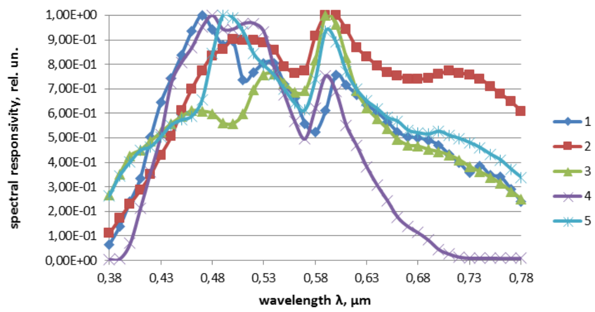

Fig. 3 – Spectral characteristics of the responsivity of the digital matrices: 1 – Kodak Z981, 2 – Sony ICX285AQ, 3 – Olympus SC50, 4 – NIKON D700, 5 – Sony IMX214

3.2 Studies of the Spectral Responsivity of the Matrices Only for the Green Channel

The measurement results of the spectral responsivity of the green channels of the matrices under study are shown in Fig. 4. The second, third and fourth matrices are the closest to the function $V(\lambda)$ of standard relative spectral luminous efficiency of monochromatic radiation.

Obviously, the Olympus SC50 Aptina MT9P006STC and NIKON D700 NC81338L matrices can be considered the best matrices for measurements using only the green channel signal. For CIE Standard Illuminant A, (that is, if there is a powerful infrared component in the emission spectrum), it is necessary to use only the NIKON D700 NC81338L camera when performing measurements.

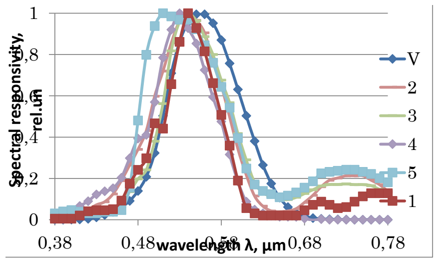

Fig. 4 – Measurement results of spectral responsivity S_λ for green channels of digital camera matrices: 1 – Kodak Z981, 2 – Sony ICX285AQ, 3 – Olympus SC50 Aptina MT9P006STC, 4 – NIKON D700 NC81338L, 5 – Sony IMX214 (curve V – spectral luminous efficiency function for photopic vision)

Based on the range of color temperatures of the sources of visible radiation, which are mainly used for illumination, the error estimate of the proposed photometer was performed for thirteen LED light sources with typical spectral characteristics that most fully cover the spectrum of light sources on the market in terms of the range of correlated color temperatures Tc: 2717; 2731; 3054; 3778; 4119; 4176; 4407; 5094; 5570; 6004; 6801; 7411 and 8376 K. The spectra of the above LEDs were measured in the Scientific and Research Laboratory "Center for Testing and Diagnostics of Semiconductor Light Sources and Lighting Systems Based on Them" (NIL TsDNDS) of V.Ye. Lashkaryov Institute of Semiconductor Physics of NAS of Ukraine [8]. For this, a specialized measuring complex [8] was used on the basis of equipment manufactured by EVERFINE Corporation (China), consisting of a high-precision HAAS-2000 matrix spectroradiometer with the capability to measure the spectral characteristics of light sources in the visible wavelength range (380 nm-780 nm), an integrating photometric sphere with a diameter of 1.0 m, and a set of DC and AC power supplies with a power meter, which allows to determine the quality of transducers/drivers of AC of power system to directly DC power of LEDs used in the light sources.

The results of calculations using the formula (5) for various LED sources in the range of color temperatures Tc of 2700 K-8400 K, the characteristics of which are given in [8], are presented in Table 1, where the first column shows the numbers of the LED sources and their color temperature, and the other five columns present the calculation results for the digital matrices under study.

From the results presented in Table 1, it follows that for the Sony ICX285AQ camera we get unacceptably large deviations from $V(\lambda)$ during measurements, but if we take into account the apparent systematic bias and introduce a correction for each of the five digital cameras under study, then the error of photometric measurements with using only the green channel will be within the range of half-difference values between the maximum and minimum values indicated in Table 1, i.e. from 22.5 % to 6 %. Without using the camera with Sony ICX285AQ matrix, then in the case of measuring LED light sources using only the green channel, the error of photometric measurements will not exceed 15 %.

Table 1 – The values of the quantity $f_1(S_z(\lambda))$ using formula (5) when measuring the spectral characteristics of digital cameras only for the green channel

LED light sources	Digital cameras				
	No. 1	No. 2	No. 3	No. 4	No. 5
1 (2731 K)	– 19.65	– 3.34 %	– 25.11 %	– 5.11 %	– 25.59 %
2 (3054 K)	– 17.03	– 59.72 %	– 24.70 %	– 3.56 %	– 21.56 %
3 (4119 K)	– 9.66	– 65.43 %	– 21.91 %	11.40 %	– 17.63 %
4 (4407 K)	– 8.54	– 67.89 %	– 21.52 %	10.90 %	– 14.25 %
5 (5094 K)	– 5.45	– 69.46 %	– 20.59 %	19.87 %	– 14.88 %
6 (5570 K)	– 4.40	– 71.62 %	– 20.01 %	18.73 %	– 10.25 %
7 (6004 K)	– 3.05	– 71.59 %	– 19.61 %	24.46 %	– 12.20 %
8 (6801 K)	– 0.51	– 72.18 %	– 18.52 %	28.95 %	– 10.74 %
9 (7411 K)	– 1.88	– 71.98 %	– 19.02 %	27.93 %	– 10.78 %
10 (8367 K)	0.91	– 74.26 %	– 17.96 %	31.02 %	– 7.18 %
11 (2717 K)	– 17.13	– 38.86 %	– 20.73 %	– 4.11 %	– 26.15 %
12 (3778 K)	– 6.81	– 29.58 %	– 13.27 %	15.59 %	– 24.72 %
13 (4176 K)	– 8.17	– 52.53 %	– 18.47 %	13.39 %	– 19.84 %
Minimum value, %	– 19.65	– 74.26 %	– 25.11 %	– 5.11 %	– 26.15 %
Maximum value, %	0.91	– 29.58 %	– 13.27 %	31.02 %	– 7.18 %
Difference, %	20.55 %	44.68 %	11.84 %	36.14 %	18.97 %
Half-dif-ference, %	10.28 %	22.34 %	5.92%	18.07%	9.48%

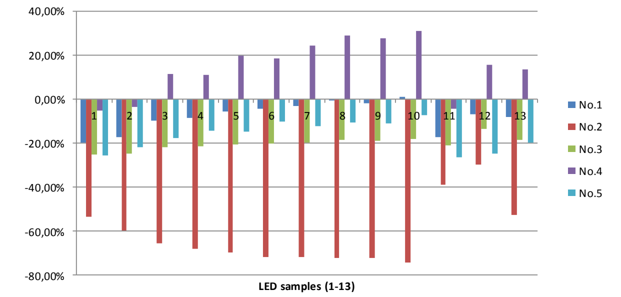

Fig. 5 – The histogram of the values of the quantity $f_1(S_z(\lambda))$ when using LED sources [8] only for the green channel of the cameras under study: No. 1 – Kodak Z981, No. 2 – Sony ICX285AQ, No. 3 – Olympus SC50 Aptina MT9P006STC, No. 4 – NIKON D700 NC81338L, No. 5 – Sony IMX214

For measurements with higher accuracy, it is necessary to use an additional correction filter to maximally approximate the resulting matrix curve to the function of relative spectral luminous efficiency of monochromatic radiation for photopic vision $V(\lambda)$.

4. DEVELOPMENT OF THE CORRECTION FILTER AND EVALUATION OF THE PHOTOMETER ERROR

4.1 Development of the Correction Filter

The spectral error of the photometer can be reduced by correcting the spectral responsivity characteristic $S_{rel}(\lambda)$ of digital camera using a correction optical filter. As an optical filter, it is proposed to use a combination of three color optical filters ZS 8, SZS 24 and ZhZS 18. The spectral transmission characteristics of the optical filter are determined by the combined use of these three glass grades, the thickness of each is selected separately. First, the spectral characteristics of each optical filter were studied, the corresponding thicknesses were calculated, correction filters were manufactured, and then their spectral responsivity was measured. At the final stage, each filter was combined with cameras and the best digital camera-filter pair was determined.

The results of the correction of the spectral responsivity of the digital cameras under study are shown in Fig. 6, and the grade and thickness of the types of glass used for each of them are given in Table 2.

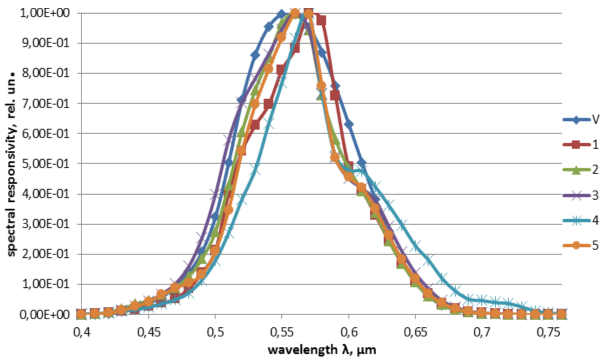

Fig. 6 – The spectral characteristics of digital camera matrices with the use of the correction optical filter: 1 – Kodak Z981, 2 – Sony ICX285AQ, 3 – Olympus SC50 Aptina MT9P006STC, 4 – NIKON D700 NC81338L, 5 – Sony IMX214 (curve V – spectral luminous efficiency function for photopic vision)

Table 2 – Thickness of glass types for the combined correction optical filter

No. of sample	Type of glass and thickness in mm			Type of camera
	SZS24	ZhZS18	ZS8	
1	8.36	3.56	1.19	Kodak Z981
2	10.65	3.23	1.37	Sony ICX285AQ
3	7.28	2.29	2.28	Olympus SC50
4	5.33	4.25	0.96	Nikon D700s NC81338L
5	5.83	4.01	1.56	Sony IMX214

Analysis of the correction of the characteristics of digital cameras with the use of optical filters with the parameters indicated in Table 2 has shown that the highest degree of correction of the spectral characteristics is provided for ICX285AQ matrix of Sony digital camera.

With the right combination of optical filter and matrix, it is possible to ensure the smallest mismatch between $S_{rel}(\lambda)$ and $V(\lambda)$. To estimate the numerical value of the correction in accordance with the existing procedures described in [5], the values $f_1(S_z(\lambda))$ for the cameras under study were calculated using the formula (5). The error of the spectral characteristics of the cameras was determined for 13 LEDs, the characteristics of which are described in [9]. With the specified parameters of filters and matrices, the error of correction is provided at a level not exceeding 5 % in the visible range. The calculation results are shown in Table 3 and Fig. 7.

Consequently, the error of photometric measurements with a wide-aperture photometer based on a digital camera using the developed correction filters does not exceed 5 %.

Taking into account the study carried out and the specific characteristics of digital cameras, which are ready-to-use products with automatic or semi-automatic exposure control, to obtain the indicated characteristics it is recommended to modify the photometer scheme – it is necessary to introduce a calibration channel. Considering that the maximum spectral responsivity of camera matrices is in the green region of the spectrum, it is advisable to perform calibration at the green wavelength. In our case, to calibrate the device, one can use a laser with a wavelength of 532 nm, which is close to the maximum spectral responsivity of the eye, installed in one light guide channel of the focon. In real conditions, laser power should be monitored and adjusted so that it would prevent the saturation of the detector matrix.

Table 3 – The values of the quantity $f_1(S_z(\lambda))$ when measuring the spectral characteristics of digital cameras with the use of the correction optical filter

LED light sources	Digital cameras				
	No. 1	No. 2	No. 3	No. 4	No. 5
1 (2731 K)	1.39 %	1.04 %	1.40 %	1.76 %	1.60 %
2 (3054 K)	2.06 %	1.54 %	2.04 %	3.43 %	2.48 %
3 (4119 K)	0.58 %	0.60 %	1.71 %	3.65 %	2.19 %
4 (4407 K)	1.15 %	0.97 %	2.03 %	4.91 %	2.69 %
5 (5094 K)	– 0.34 %	0.06 %	1.77 %	3.50 %	2.47 %
6 (5570 K)	0.37 %	0.47 %	2.01 %	5.19 %	2.87 %
7 (6004 K)	– 0.64 %	– 0.13 %	1.75 %	3.89 %	2.53 %
8 (6801 K)	– 1.28 %	– 0.55 %	1.60 %	3.60 %	2.46 %
9 (7411 K)	– 0.49 %	– 0.03 %	1.69 %	4.35 %	2.37 %
10 (8367 K)	– 1.32 %	– 0.58 %	1.80 %	4.24 %	2.94 %
11 (2717 K)	– 0.38 %	– 0.34 %	– 0.32 %	– 0.13 %	0.40 %
12 (3778 K)	– 3.88 %	– 2.72 %	– 1.88 %	– 2.22 %	– 1.11 %
13 (4176 K)	– 0.91 %	– 0.53 %	0.28 %	1.84 %	0.76 %
Minimum value, %	– 3.88 %	– 2.72 %	– 1.88 %	– 2.22 %	– 1.11 %
Maximum value, %	2.06 %	1.54 %	2.04 %	5.19 %	2.94 %
Difference, %	5.94 %	4.27 %	3.92 %	7.41 %	4.05 %

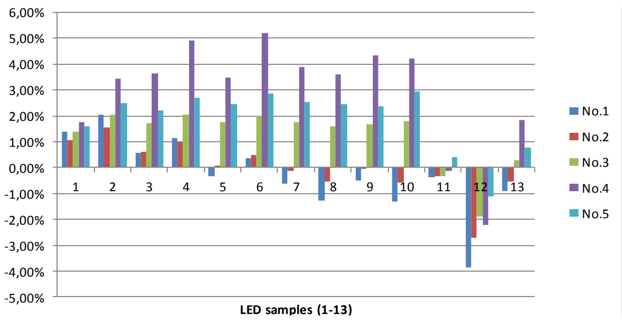

Fig. 7 – The histogram of the values of the quantity $f_1(S_z(\lambda))$ when using LED sources [9] for recording the resulting spectral characteristics of the cameras under study with the correction optical filter: No. 1 – Kodak Z981, No. 2 – Sony ICX285AQ, No. 3 – Olympus SC50 Aptina MT9P006STC, No. 4 – NIKON D700 NC81338L, No. 5 – Sony IMX214

5. CONCLUSIONS

In order to reduce the error of the results of measurement by a wide-aperture photometer based on a fiber-optic focon, when using matrices of modern digital cameras to record the signal, an installation was developed and the spectral characteristics of digital cameras were measured. It was shown that the error of photometric measurement using only the "green channel" of a digital camera would be in the range from 22.5 % to 6 %. In order to reduce the measurement error to 5 % using a wide-aperture photometer based on a digital camera, the correction filters were developed. According to the results of the study of a wide-aperture photometer based on the matrix of a digital camera, recommendations were developed for the improvement of the photometer. The developed photometer allows, due to its wide aperture, to measure the photometric body of emitters, including those that cannot be rotated according to operating conditions.

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Підвищення точності широкоапертурного фотометра на основі цифрової камери

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Для зменшення витрат і часу тестування освітлювальних характеристик світлодіодних джерел запропоновано і запатентовано конструкцію фотометру на основі волоконно-оптичного фокона для вимірювання просторового розподілу випромінювання без обертання. У роботі представлені результати досліджень спектральних характеристик цифрових камер з ПЗС-матрицями, включеними в такий широкоапертурний фотометр, як матриця фотоприймача. Спектральні характеристики матричних фотоприймачів досліджувалися відповідно до процедури стандартизації CIE (ISO/CIE 19476: 2014). Відхилення отриманих спектральних характеристик від стандартної функції відносної спектральної світлової ефективності монохроматичного випромінювання для фотопічного зору V(λ) визначило похибку вимірювання фотометричного тіла світлових пристроїв. Встановлено, що вимірювання спектральних характеристик матриць цифрових камер тільки на «зеленому каналі» недостатньо, оскільки невідповідність між результатом вимірювання та функцією відносного спектрального світлового ефекту монохроматичного випромінювання для фотопічного зору знаходиться в діапазоні від 6 % до 22.5 %. Виходячи з діапазону колірних температур джерел видимого випромінювання, які в основному використовуються для освітлення, оцінка похибки запропонованого фотометра була виконана для тринадцяти світлодіодних джерел з типовими спектральними характеристиками, які найбільш повно охоплюють спектр джерел світла на ринку з точки зору діапазону корельованих колірних температур T_C: 2700-8400 K. Для забезпечення заданої точності фотометрів шляхом корекції характеристики спектральної чутливості $S_{rel}(\lambda)$ цифрової камери використовують оптичний фільтр корекції з відповідними характеристиками. Як оптичний фільтр пропонується використовувати комбінацію трьох кольорових оптичних фільтрів ЗС 8, СЗС 24 і ЖЗС 18. Характеристики спектральної передачі оптичного фільтра визначаються комбінованим використанням цих трьох сортів скла, товщиною кожного вибирається окремо. Показано, що з використанням розробленого коригувального фільтра, який представляє собою комбінацію 3 типів скла, можна зменшити похибку спектральних вимірювань до 5 %.

Ключові слова: Фотометр, Світовий потік, Спектральна чутливість, Цифрова камера.