Journal of Engineering Research and Reports

20(10): 65-73, 2021; Article no.JERR.70912
ISSN: 2582-2926

Development of High Sensitivity Illuminance Meter for Measurements in Lighting Engineering and Photometry

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/JERR/2021/v20i1017390
Editor(s):
(1) Dr. Neha Munjal, Lovely Professional University, India.
Reviewers:
(1) Annan Jiang, Dalian Maritime University, China.
(2) I. Gede Tunas, Universitas Tadulako, Indonesia.
Complete Peer review History: https://www.sdiarticle4.com/review-history/70912

Original Research Article

Received 12 May 2021
Accepted 17 July 2021
Published 22 July 2021

ABSTRACT

Possible ways of solving the main problems arising in development, manufacture and calibration of high-sensitivity Illuminance meters are considered. Methods of reducing the lower limit of measurement of Illuminance to 10^{-5} lux are proposed. Errors of correcting light filters of different manufacturing methods are estimated. The calculations of measurement errors of illuminance from modern energy-saving lamps and LEDs are made.

Keywords: Illuminance meter; responsibility; correcting filter; calibration; measurement errors.

1. INTRODUCTION

Widely used luxmeters have measurement limits from one lux to more than 100,000 lux, providing measurement of illuminance from various sources. Luxmeters are used in all lighting systems [1].

The light intensity is measured by measuring illuminance and distance to source. Luninance is calculated from the measured illuminance and angle of observation, or through the area of luminous element and the distance to it. Measurement of indicatrix light intensity with conversion to radiation flux and retroreflective coefficients requires use of a high-sensitivity

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luxmeter. The measurement of illuminances of less than one lux is necessary for certification of dark rooms and measurements on darkened ones streets. Also, high-sensitivity luxmeters are necessary for measurements in photometric laboratories, for example, when measuring visual transmittance, reflectance, and retroreflective coefficients [2,3]. The main requirements for the luxmeter are: the constant Luminance factor at different lighting angles, the minimum spectral component of measurement error, and required measurement limits. The luxmeter is the simplest photometric device. The principle of operation, design and calibration methods are given in the main monographs on photometry [4-8]. The designs of specific types of luxmeters are given in the company catalogs. Information about the luxmeter currently being produced in Russia is given in [1].

When the light flux hits receiving area of luxmeter at an angle to normal to surface of receiver, its projection works in this direction. The dependence of projection on angle of incidence of light is determined by the law of cosine, so this dependence is often called cosine. The luminance factor of receiving surface remains constant. The constancy of luminance factor in all directions is ensured either by open receiving surface of photodetector, or by installation of a milk glass in front of receiver. Milk glass has a constant luminance factor within angles of 60-70 degrees from normal to surface. The drop in luminance factor at large angles is compensated by hit of part of light on side surface of milk glass. To do this, the milk glass is partially raised above the body.

2. CORRECTING LIGHT FILTER

There are three possible ways to calculate the correcting light filter. Method 1-selection of colored glasses that allow to correct spectral curve of photo receiver, bringing it closer to curve of spectral light efficiency of standard photometric observer MKO *V (λ)* [9]. Method 2-use of light filters that cut off short-wave and long-wave regions of spectrum of radiation source. Method 3 - formation of curve *V (λ)* by color light filters for receiver with responsibility in entire visible region of spectrum. From the very beginning of development of correcting light filters in 20-30 years of 20th century, the error of correction was estimated using a type *A* source [9], which well imitates incandescent lamps. The assessment was carried out by integral method. The curve of spectral responsibility of photo receiver was multiplied by curve of relative spectral power of radiation source *A* for all measurement intervals, and results were summed up. Similar calculations were performed for the curve *V (λ*). The ratio of obtained sums gives relative error of correction. Currently, due to widespread use of LED and fluorescent lamps, it is advisable to estimate the error of correcting under equal-energy spectrum of radiation source. In this case, the area under spectral curve of corrected photodetector is divided by the area under curve *V(λ)* . In the article, the integral estimation of correction error is made by this method. In addition to integral estimate, it is advisable to use the ratio or difference of spectral responsibilities of receiver and curve *V (λ)* at individual points of spectrum. The difference is preferred, since it is involved in calculation of areas under curves.

Mass-produced in the USSR luxmeters of types Yu117, etc. had a selenium photocell as a radiation receiver without a correcting light filter. The correction of spectral responsibility in long-wave region of spectrum was provided by a photocell, in short-wave region of spectrum by type *A* radiation source. The error of correction under source *A* for them did not exceed 10-15%. Similar results were obtained for vacuum multi-alkaline cells and photomultipliers used in luminance meters.

Correction according to method 1 gives good results for selenium solar cells, the spectral curve of which is close to the curve *V (λ)* . Developed in the 20-30s of last century, corrective light filters have good characteristics when evaluated through an equal-energy spectrum. The light filter recommended for selenium solar cells [10] made of ZS8 (green) glasses with a thickness of 1.9 mm and ZZS18 (blue) glasses with a thickness of 2.1 mm has a small error of correction through equal-energy spectrum (Table 1). The correction error of selenium solar cell (Se + filter in Table 1), made by author according to the catalog data, corresponds to the best samples.

Silicon photodiodes are widely used due to their low dark current, extended spectral range, and work with bias voltage, which increases speed and responsibility. However, the spectral curve of a silicon photodiode is not well suited for a correcting filter. At the end of the 70s, work was carried out on the selection of corrective light filters for the FD7K or FD24K silicon photodiode used in serial photometers according to method 1. The average spectral responsibility curve for

35 photodiodes and two extreme curves for the photodetectors with the lowest and highest responsibility were used for calculation. According to calculation results, the best correcting filter is obtained from glasses 3C-8, J3C-I8, C3C-23. The light filter transmittance is 0.7-0.8. for all considered filter combinations, a weak dependence on type of spectral responsibility of photodiodes was observed. The correction error for category 2 glasses deteriorated from 5 to 10 %, depending on the melting of glasses. It should be noted that real filters can have a large correction error associated with spread of spectral curves of photodiodes and technological difficulties of manufacturing and assembling photodetector.

Currently common luxmeters of company TKA (Russia) use a correcting light filter to a silicon photodiode by the 2 method using orange and blue glasses. Such receivers made by author with glasses of the OS6 brand with a thickness of 3.5 mm and SZS21 with a thickness of 1 mm had a correction error for equal-energy spectrum of 15.9 %. (Table 1).

The author of article developed a correcting light filter according to the 3rd method. More than 10 combinations of colored glasses were tested experimentally. The best combination was obtained from glasses ZS8 with a thickness of 0.75 mm, ZHZS18 with a thickness of 1.9 mm and SZS21 with a thickness of 1.5 mm. The light filters were tested with photodiodes FD263 and FD155. The spectral curve of light filter (Fig. 1) is similar to the curve *V (λ),* but skewed to compensate for the drop in responsibility of photodiodes to the short-wave region of visible radiation spectrum (Fig. 1).

In total, several dozen copies of photodetectors were manufactured. Photodiodes and filter glasses were not selected very carefully. The correction error for the equal-energy spectrum ranged from zero to 15% for all types of photodiodes. (Table 1). Of the total number of measured receivers, there were 5 receivers in the range 0-2%, 8 receivers in the range 2-5%, 3 instances in the range 5 - 10%, and only 2 receivers in the range 10 - 15%.. At the same time, maximum difference between points of same name of spectral curves of photodetectors and curve *V(λ)* was estimated. This estimate complements the integral estimate, not allowing curves to shift relative to each other. The greatest deviation from the *V(λ)* curve for most receivers was at a wavelength of 540 nm.

3. PHOTO RECEIVING DEVICE

In luxmeters and exposure meters produced in the USSR, a galvanometer was used as a recording device. In addition to low responsibility, such devices had non-linear scale. This is due to the fact that a voltage drop occurs on internal resistance of galvanometer, which is subtracted from total voltage on selenium photocell or photodiode. Reducing voltage leads to decrease in low limit at the top of instrument scale. Noticeable deviations from linear dependence occur at voltage greater than 10 mV. Devices with bias voltage on photodiode are free from this drawback. However, in this case, the dark current increases, and measurement limits are reduced. To eliminate these shortcomings, use of an operational amplifier in circuit of device allows. In a circuit with an operational amplifier without additional bias on photo receiver, voltage on it is kept constant with high accuracy when current through photo receiver changes [11]. This allows getting a linear scale in all measurement limits and a minimum dark current that determines the lower limit of measurement. The upper limit is limited by current saturation of photo receiver, which does not exceed 10 - 20 μA for most silicon photodiodes and selenium photocells. In scheme of luxmeter [12] developed by author, measurement limits were switched by resistances in feedback circuit of operational amplifier, which simultaneously served as load resistances of photo receiver. Load resistors varied in range of 100 kOm – 5 MOm for all photodiodes and selenium photocells, and up to 50 MOm for low dark current samples. Such a luxmeter (Fig. 2) has responsibility of 5 10^{-4} Lux/mV with a selenium cell with diameter of 20 mm. With the common used voltmeter-tester VM830, this corresponds to a count of 10 divisions. The upper limit of measurement is 50 lux. For device with photodiode FD263 type with correcting filter and a milk glass, the measurement limits are 5 10^{-3}-500 lux.

A more sensitive luxmeter is built with a vacuum photocell F22 type. The photocell has anode in form of grid, located at a distance of 2-3 mm from the photocathode, which allows working with a supply voltage of 12 V. The photocell is included in the circuit with the same operational amplifier. Load resistances are switched between 100kOm and 1GOm. The luxmeter is powered by two 9-volt batteries (Fig. 3). The responsibility at lower limit of measurement is 2 10^{-5} Lux/mV. The upper limit is 200 lux. The correcting filter is made according to the 2nd method from OS6 glass.

Table 1. Errors of correcting experimental samples by different ways

Metod of correcting	Sample number	Errors of equal energy spectrum, %	Maximum difference between curves, %	Wavelength of maximum difference, nm
Ю117 without flter	*Se*	88	59	500
way 1	Se+filter	3,6	13,8	500
Way 2	*Si*	15,9	10,0	500
way 3 *Si*	1	1,6	5,8	500
	2	0,3	3,5	660
	3	4,9	6,8	620
	4	0,4	3,5	600
	5	3,4	9,6	600
	6	3,4	9,8	580
	7	3,6	7,5	580
	8	5,6	8,6	580
	9	4,1	8,3	580
	10	7,3	13	540
	11	0,7	3,9	580
	12	7,3	1	520
	13	12,1	2,3	540
	14	8,4	12	540
	15	1,5	5,8	500
	16	0	8,9	500
	17	4,3	8,8	620
	18	2,8	1,2	500

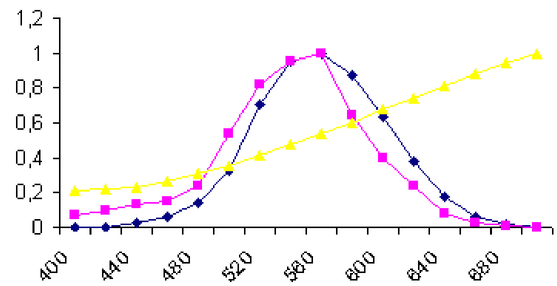

Fig. 1. Spectral characteristics of correcting filter (squares), the curve *V(λ)* (rhombuses)

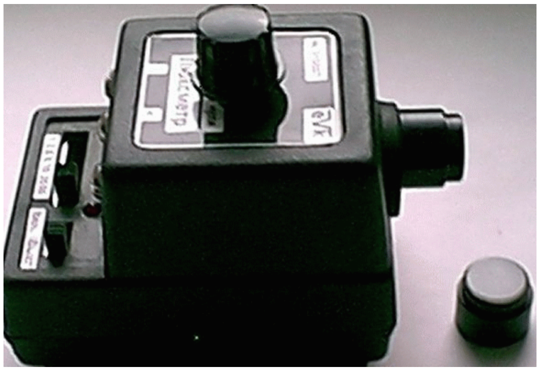

Fig. 2. Photo of luxmeter with silicon photodiode and milk glass

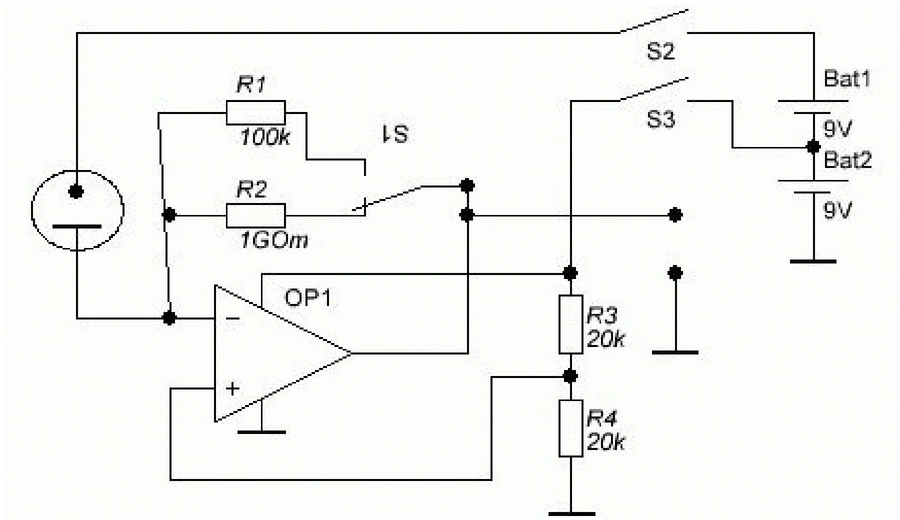

Fig. 3 Scheme of connection to power sources of luxmeter with vacuum photocell

The angular field of view of device is 90 -120^0. If the radiation source that creates measured illumination is remote and not very extended and the direction is known to it, then angular field of view of the device may be narrowed, and responsibility increases accordingly. In this case, a collecting lens is placed in front of luxmeter. Then calculation will not include the area of receiver, but the area of lens, which can be larger by 1-2 orders of magnitude. This is the most optimal way to dicrease low limit.

The obtained results allow to solve problems of insufficient sensitivity of illuminance meters, described in [2,3].

It is not always possible to increase sensitivity of luxmeter by increasing the area of radiation receiver. This increases the dark current of receiver and final effect may be reversed. Consider another way to increase receiving area of luxmeter. It is can be use the property of an operational amplifier to keep voltage on photodiode constant; it can include several photodiodes in series in the circuit. At the same time, it was found that the equivalent dark current of photodiode group decreases and it is possible to increase load resistance with increase in responsibility of device. Experiments were carried out on photodiodes FD263 type with a receiving pad size of 3x3 mm and a lens with diameter of 5 mm. (Table 2). Photodiodes were switched on in series between two inputs of operational amplifier without additional bias voltage and were illuminated all together. The light responsibility of all assemblies was the same with error of ±10%. In assembly of two photodiodes, if close any photodiode from radiation, responsibility decreases by 10 to 20 times. The same is observed if close any photodiode in assembly of more photodiodes. At the same time, zero offset voltage at output of operational amplifier was measured at different resistances in feedback circuit of amplifier (Table 2). Resistances are proportional to dark current of photodiode group.

The bias voltage at the output of amplifier can be compensated by additional voltage source as long as it is less than output saturation voltage of amplifier. With increase in feedback resistance, which simultaneously serves as load resistance of photodiodes, responsibility of device increases proportionally. As can be seen from the table, the gain in responsibility with two photodiodes is 4 times, with four-more than 5 times. For germanium photododes FD3G type, gain was 2 times less, and load resistance was 200 times less. To obtain uniform zone characteristic, assembly of six photodiodes is placed in hemisphere with radius of 18 mm. The entrance hole is negative lens with light diameter of 8 mm. The responsibility is 9 times less than that of single photodiode. Taking into account the fact that area of input hole is increased by 2.5 times, and responsibility can be increased by 5 times, it turns out device with a slightly higher responsibility and with improved zone and angle characteristics. Such device is good for small receivers, for example, for infrared photodiodes. The considered method can reduce low limit of luxmeter by at least 5 times.

Table 2. Dependence of zero offset voltage on photodetector output on load resistance of radiation receivers and number of photodiodes

Number uf photodiodes	Zero offset in mV at load resistance, MOm			
	1100	**492**	**222**	**62**
1	1100	480	239	89
2	300	127	56	14
4	200	92	44	20
6	240	100	47	10

4. CALIBRATION

There are two ways to calibrate luxmeters: by a reference light source and by a reference receiver with known spectral responsibility at wavelength of 555 nm. Calibration by the source – an incandescent light-measuring lamp is performed on photometric bench. The calibration process is time-consuming, as it is necessary to make sure that there is no additional signal from the scattered light. Test is performed by measuring at different distances. In case of high-sensitivity luxmeters, it is necessary to use pre-measured additional neutral light filters. Sometimes it is necessary to check the incandescent lamp's not completely attenuated IR radiation. For calibration of highly sensitive luxmeters, it is more convenient to use the second method. In an installation with a monochromator and an incandescent lamp, spectral responsibility of calibrated luxmeter is measured at a wavelength of 555 nm, corresponding to maximum of curve *V(λ).* Mechanical equivalent of 683 *Lm /W* is divided by measured responsibility in *A / W*. The result of calculation in *Lm / A* is divided by the area of receiving element of luxmeter in m^2 and result of dividing in *Lux/A* is obtained. Dividing the obtained value by load resistance in photo receiver circuit, the final value of division in *Lux/V* for a specific voltmeter is obtained. At the same installation, spectral characteristic of luxmeter is measured to estimate the spectral component of measurement error. Calibration process by the second method is simple and has no additional errors. The main difficulty is in calculating the area of receiving element. The most sensitive luxmeters do not have an input milk glass. Usually, area of transparent glasses of correcting light filter is larger than area of radiation receiver, especially photodiodes. Therefore, when measuring spectral responsibility, the entire receiving element must be illuminated. This is not always possible in the case of large receiving elements. Therefore, calculation should take into account zone characteristic of luxmeter. Typical values of responsibility of receiving elements at wavelength of 555 nm, are 0.11 *A / W* for selenium solar cells, 0.04 *A / W* for milk glass photodiodes and 0.07 *A / W* for multi-alkaline cells. If measurements are made correctly, calibration results for method 1 and 2 match well. The calibration error of spectral responsibility of photo receiver does not exceed 3%. Taking into account error of reference receiver, the total calibration error is 4 – 7%, which is usually less than for the reference source.

5. ILLUMINANCE MEASUREMENT ERRORS

The total error of illuminance measurement has three main components: the random error of instability of sampling, the non-excluded systematic error of responsibility calibration, and spectral error due to discrepancy between curve of spectral responsibility of luxmeter and curve *V(λ)* . As experience of measurements shows, the random component of measurement error is small in comparison with other two and it will not consider. The calibration error, as shown above, in accordance with the verification scheme of GOST 8.023 is 7-15% for working measuring instruments.

It is of interest to estimate the spectral component of error in measuring illuminance from modern energy-saving lamps. Low-power fluorescent lamps have a radiation spectrum in form of separate lines (Fig. 4). The ratio between the individual lines of lamps of different companies varies, as can be seen from the measurements carried out by the author and calculation of coordinates of chromaticity and color temperature according to GOST R 55703-2013 [13]. In LED lamps, white color is obtained from luminescence when excited by blue color. Therefore, both spectral components are present in radiation spectrum (Fig. 5).

Depending on quantum yield of luminescence, warm light sources with a color temperature of *T* = 2700^0 *K* and cold light sources with a color temperature of 4300^0 *K* or more are distinguished. Similarly to calculations of correcting light filter, the error of measuring illuminance from such sources is calculated. To do this, the normalized spectral curve of used luxmeter was multiplied by light source curve and the area under resulting curve was calculated. The same calculations were performed for curve *V (λ)*. Difference between unit and ratio of obtained areas determined the error in measuring illuminance. For comparison, calculations were also made for source *A*. The spectral component of error in measuring illuminance from such sources (Table 3).

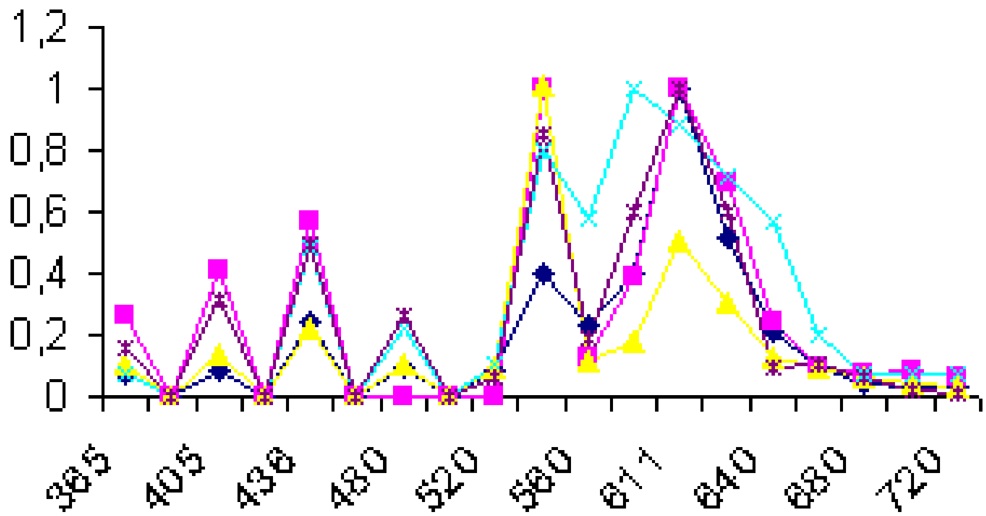

Fig. 4. Spectral distribution and chromaticity coordinates of Miller firm 11W fluorescent energy-saving lamps, y=0.558, x=0.409; Navigator 11W, y=0.532, x=0.416; Philips 12W, y=0.527, x=0.429; Foton 11W, y=0.52 x=0.421; Sholtz 11W, y=0.48, x=0.473. The lamps emit separate lines in spectrum, which are connected by straight lines for clarity

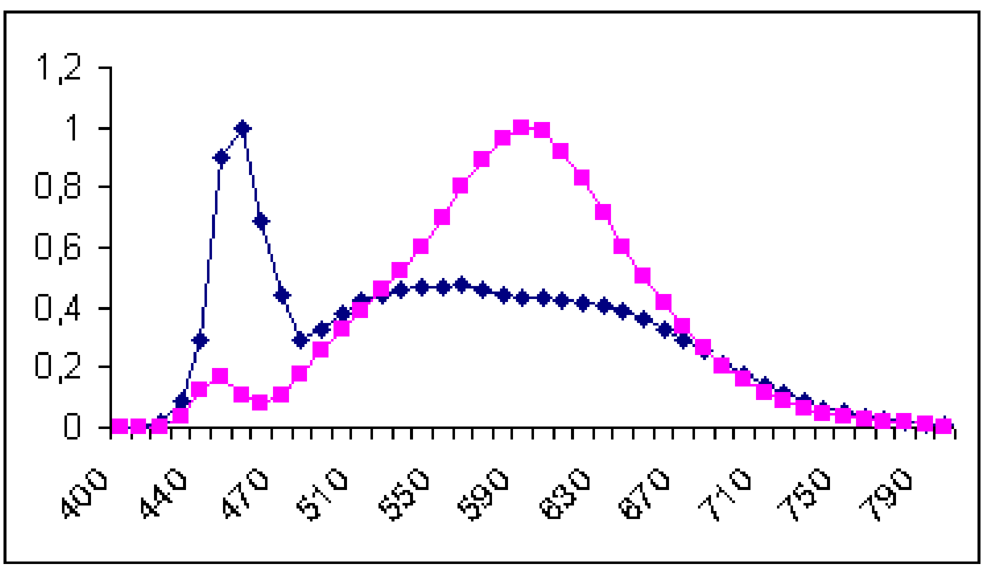

Fig. 5. Spectral distribution of radiation of warm light T = 2700^0 K (squares) and cold light T = 5800^0 K (diamonds). LED lamps

Table 3. Errors in measurement of illuminance from various light sources for *GOI Se* selenium photocell produced in 50 years, the Si(2) silicon photodiode corrected according to method 2, the *Kuv Si* sample according to method 3 of correction, and the *Se new* selenium photocell manufactured in 90 years according to optical glass catalog

Receiver	Equal energy spectrum, %	Source A, %	LED warm, %	LED cold, %	Lamp, %
GOI Se	17,9	14,3	13,8	16,7	4-75
Si (2)	16,1	14,4	10,3	14,3	8-55
Kuv Si	3,2	6,6	3,6	8,2	6-39
Se new	3,5	0,8	0,002	3,5	19-94

Approximately corresponds to error from incandescent lamps and LED sources of warm color and more for cold light sources and fluorescent lamps. When evaluating according to method 3, the average correction error curve of receiver was taken into account (No. 4 in Table 1). In case of fluorescent lamps, calculation was made for all curves in Fig. 5. The table shows the extreme values of errors. The calculations show that spectral component of illuminance measurement error prevails over other components. At the same time, if it is small for one type of source for a particular luxmeter, then it is much larger for other sources. Therefore, each correction method is best suited to a particular type of radiation source. In general, better results are obtained for more expensive method 3 and for selenium solar cells fitted according to method 1. Taking into account all components, the total error of measuring illuminance is 12-20%, and for cases of combinations of a luxmeter and fluorescent lamps, it is even greater.

5. CONCLUSIONS

The spectral component of illuminance measurement error from modern energy-saving lamps is greater than from incandescent lamps. The existing colored glasses do not allow to produce a corrective light filter of required quality .It is proposed to calibrate for each color and light source separately. The color can be estimated by the operator's eye. The error in determining the color will be less than the error from applying a corrective light filter. In this case, a corrective light filter is not needed, it is only necessary to apply a cutting light filter.

A method for reducing the dark current of photodiodes by several times is proposed, which allows reducing the measurement limit of luxmeter to 10^{-5} lux. A portable luxmeter with a vacuum photocell has been developed, in which the lower limit of luxmeter measurement is reduced by 10 times compared to photodiodes.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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