Diffuse Reflectance Spectrophotometers Based on C12880MA and C11708MA Mini-Spectrometers Hamamatsu

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Abstract

Diffuse reflection spectroscopy with spatial resolution is a promising direction of non-destructive control of the properties of a number of scattering fine-dispersed materials, including food products. It can find wide practical application only in the presence of compact, easy-to-use and inexpensive spectrophotometric equipment. The aim of the article is to investigate the possibility of creating portable spectrophotometers based on Hamamatsu mini-spectrometers, which work together with modern computing facilities.

The schematics for connecting the C12880MA and C11708MA mini-spectrometers to portable computing devices are reviewed. Shows the feasibility of using a small-sized microprocessor board ARM STM32F103C8T6 (Blue pill) on the chip STM32F103C8T6. Its use in the connection scheme has simplified data exchange with the control computer via USB interface and the formation of all the signals that are needed to control the mini-spectrometer.

Two experimental samples of spectrophotometers based on C12880MA and C11708MA mini-spectrometers and STM32 microprocessors were created and their characteristics were studied. The calibration procedure and features of the software for these spectrophotometers are presented. The described features ensure the efficiency of software modification for the spectrophotometric problem to be solved. The presence of distortions of the registered spectra in the short-wave part of the spectral range of C12880MA was revealed. They arise due to focusing by the concave diffraction grating of a part of the radiation scattered by it into zero order.

Approbation of developed portable spectrophotometers based on Hamamatsu mini-spectrometers indicates the possibility of their use in portable spectrophotometric equipment and devices for spectral control of optical properties of scattering materials. The described calibration technique allows you to determine the range of the spectrum, in which the distortions of the recorded spectra are minimal. The proposed solutions significantly reduce the cost of diffuse reflectance spectroscopy devices with spatial resolution and expand the possibilities of their use in various branches of science and industry.

Keywords: diffuse reflection, mini-spectrometers, spectral sensitivity, spectrophotometers, calibration of spectrometers.

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Спектрофотометры диффузного отражения на основе мини-спектрометров C12880MA и C11708MA Hamamatsu

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Спектроскопия диффузного отражения с пространственным разрешением – перспективное направление неразрушающего контроля свойств ряда рассеивающих мелкодисперсных материалов, в том числе и продуктов питания. Она может найти широкое практическое применение только при наличии компактной, простой в применении и недорогой спектрофотометрической техники. Цель статьи – исследование возможности создания портативных спектрофотометров на основе мини-спектрометров Hamamatsu, которые работают в комплексе с современными вычислительными средствами.

Рассмотрены схемы подключения мини-спектрометров C12880MA и C11708MA к портативным вычислительным устройствам. Показана целесообразность использования малогабаритной микропроцессорной платы ARM STM32F103C8T6 (Blue pill) на чипе STM32F103C8T6. Её использование в схеме подключения позволило упростить обмен данными с управляющим компьютером по USB интерфейсу и формирование всех сигналов, которые необходимы для управления работой мини-спектрометра.

Созданы два экспериментальных образца спектрофотометров на основе мини-спектрометров C12880MA и C11708MA и микропроцессоров STM32 и исследованы их характеристики. Приведены методика градуировки и особенности программного обеспечения этих спектрофотометров. Описанные особенности обеспечивают оперативность модификации программного обеспечения под решаемую спектрофотометрическую задачу. Выявлено наличие искажений регистрируемых спектров в коротковолновом участке спектрального диапазона C12880MA. Они возникают за счёт фокусировки вогнутой дифракционной решёткой части рассеиваемого ей излучения в нулевой порядок.

Апробация созданных портативных спектрофотометров на основе мини-спектрометров Hamamatsu указывает на возможность их применения в портативной спектрофотометрической технике и устройствах спектрального контроля оптических свойств рассеивающих материалов. Описанная методика градуировки позволяет определять диапазон спектра, в котором искажения регистрируемых спектров минимальны. Предлагаемые решения позволяют существенно снизить стоимость устройств спектроскопии диффузного отражения с пространственным разрешением и расширить возможности их использования в различных отраслях науки и производства.

Ключевые слова: диффузное отражение, мини-спектрометры, спектральная чувствительность, спектрофотометры, градуировка спектрометров.

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Introduction

Optical spectroscopy is widely used in the analysis and control of the composition of various materials and media. Modern microelectronics makes it possible to create portable colorimeters and spectrophotometers, for example, KNFIR-170A (China), which are designed to determine the diffuse reflectance spectra of various materials (granules, powders, fabrics, composite materials, etc.). Modern microelectronics makes it possible to create portable colorimeters and spectrophotometers, for example, KNFIR-170A (China), which are designed to determine the diffuse reflectance spectra of various materials (granules, powders, fabrics, composite materials, etc.) in the visible and infrared regions of the spectrum [1]. Several companies manufacture computerized spectrophotometric systems for measuring diffuse reflectance spectra of inhomogeneous materials. They are equipped with a built-in integrating sphere, for example, the B&W Tek i-Spec Plus series [2]. An example of their use is the operational non-destructive control of the content of nicotine, sugar and chlorides in tobacco based on original algorithms for multiplicative scattering correction.

The use of an integrating sphere is inconvenient at solving many problems of operational optical control of the composition of finely dispersed materials. It is also important to take into account the influence of the unknown coefficient of scattering of the incident radiation by their surface. Therefore, some researchers are developing a new direction of optical control of composite materials and biological tissues, which is called diffuse reflection spectroscopy of light radiation with spatial resolution [3–7]. It is based on the use of narrow beams of probing and backscattered radiation, which are perpendicular to the reflecting surface of the controlled medium. Several reflection spectra are recorded at different distances between the beams. As the amount of data obtained increases at comparison with traditional reflectance spectroscopy, the possibility of creating new methods for processing the recorded spectra appears [5–9]. The reliability of determining the structure of the medium and the volume concentration of the controlled chromophores should also improve significantly.

Existing portable spectrophotometric equipment usually uses mini-spectrometers based on a symmetric Czerny–Turner optical scheme using a concave diffraction grating and a array of photo-

detectors. The optical path length of the diffracted radiation in these minispectrometers must be at least 70 mm to provide good spectral resolution (on average about 1 nm). This limits the miniaturization of the equipment under discussion. In cases where the device for surface illumination and registration of diffusely reflected radiation must be miniaturized, fiber-optic technique is often used. It is used to inject light radiation into the material sample under study and transmit the reflected radiation to the entrance slit of the spectrometer [4, 5]. The disadvantage of this scheme is the instability of the value of the recorded fluxes, which is caused by uncontrolled bends of the optical fibers during measurements. To eliminate this disadvantage and reduce the cost of equipment, it is necessary to abandon the use of optical fibers and use mini-spectrometers, production of which was mastered by Hamamatsu Corporation. These spectrometers have small dimensions of $20.1 \times 12.5 \times 10.1$ mm^3 (C12880MA) [10] and $27.6 \times 16.8 \times 13$ mm^3 (C11708MA) [11] and operate in the visible and near-infrared spectrum ranges. They can be used in the creation of compact spectrophotometric devices with limited spectral resolution, which is designed to control the optical characteristics of condensed media with smooth changes in the spectral absorption coefficient of radiation $\mu_a(\lambda)$.

The discussed methods of optical reflectance spectroscopy can find wide practical application in industry, agriculture, biology and medicine only if compact, easy-to-use and inexpensive spectrophotometric equipment is available. Therefore, the aim of the work is to study the possibility of creating portable spectrophotometers based on Hamamatsu C12880MA and C11708MA mini-spectrometers. Also the problems of their complexation with modern computer equipment to provide their expansion of possibilities and convenience of use are considered.

Connection diagrams for mini-spectrometers

The C12880MA and C11708MA spectrometers are miniature devices containing an entrance slit, a concave focusing reflective diffraction grating with a flat field of the formed image of slit [10, 11]. In the plane of the generated image is a CMOS line matrix of photodiodes. The supply voltage of these spectrometers is +5 V. Therefore, TTL control signals must be applied to the outputs of the electronic circuitry of these spectrometers. At the analog

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output of the spectrometer a series of video pulses are formed, the amplitude of which is proportional to the exposure time of the fra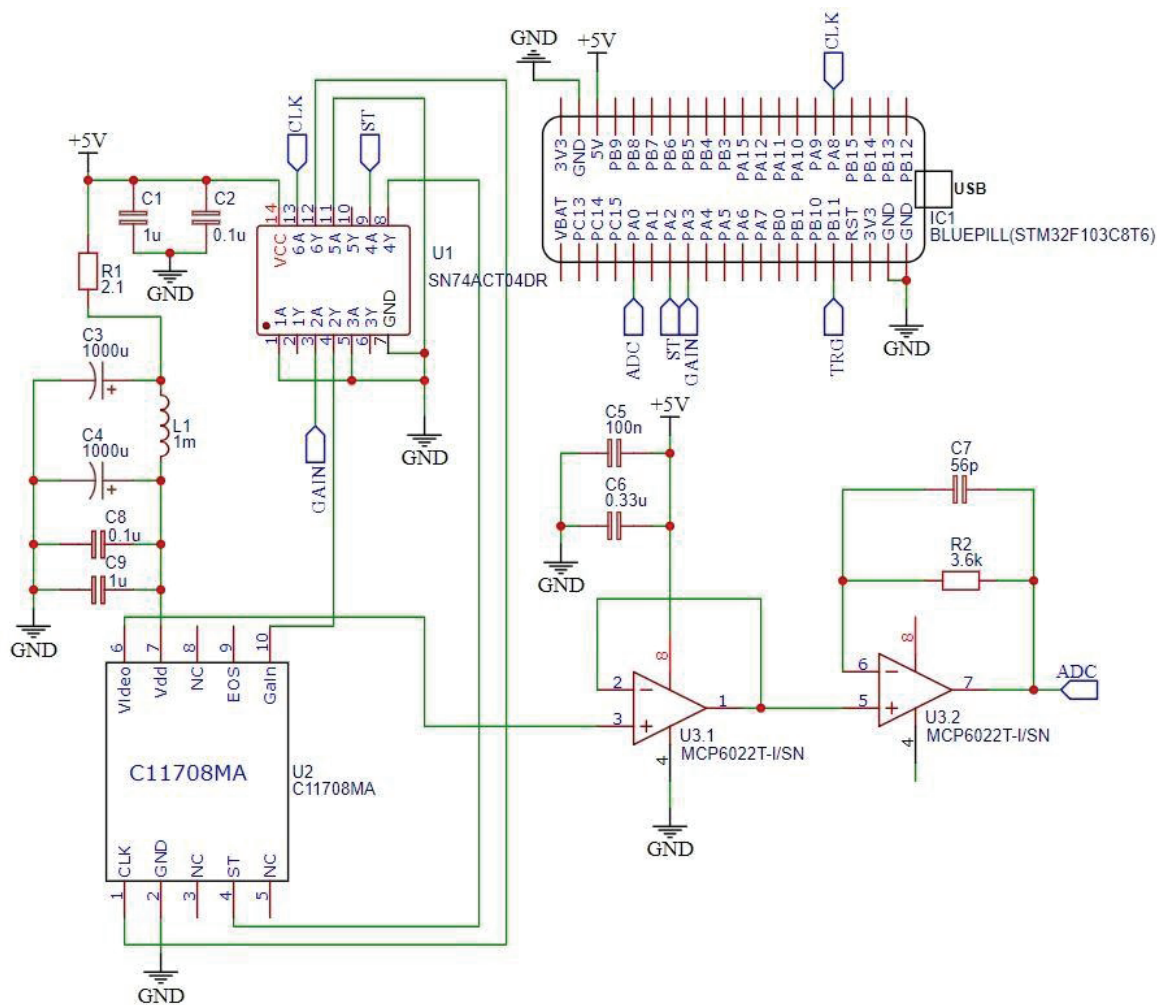me and the photocurrents that are produced by the light-sensitive elements of the line matrix of photodiodes. The best way to connect these spectrometers to a computer is to use a microprocessor-based device with built-in analog-to-digital converters (ADCs).

Market analysis of microprocessor boards shows that the smallest size at a low price has a microprocessor board ARM STM32F103C8T6 STM32 (Blue pill) on a chip STM32F103C8T6, which can be powered from a USB computer port. This board has good performance, all the necessary connectors and interfaces for connecting to a computer and other devices, including the programmer, as well as two built-in 12-bit ADC and 3 timers. The connection diagrams of the C12880MA and C11708MA, developed by the authors of the article, are shown in Figure 1. They are based on Hamamatsu's recommended standard schemes for connecting the necessary external components to them [10, 11].

The microprocessor generates the required CLK and ST logic signals, which are necessary to control the operation of the electronic units of the minispectrometers according to the Hamamatsu recommended timing diagram. Level matching of digital TTL signals used in the microprocessor (from 0 to +3.3 V) and mini spectrometers (from 0 to +5 V) provides the level converter U1 on the SN74ACT04DR. The video signal generated by the spectrometer is fed to the ADC input of the microprocessor through two broadband analog repeaters in series, based on a dual MCP6022-I/SN op-amp. The Blue pill board contains a built-in stabilized power supply with a voltage +3.3 V, which provides the necessary conditions for the stable operation of the built-in ADC with a conversion range from 0 to +3.3 V. The video signal of the mini-spectrometer C12880MA can be changed in the range from 0.3 to 4.3 V. Therefore, in its circuit at the output of the first analog repeater on the operational amplifier a resistive signal divider R3, R4 is used, which ensures the coordination of the variation range of the video signal with the conversion range of the ADC microprocessor.

a

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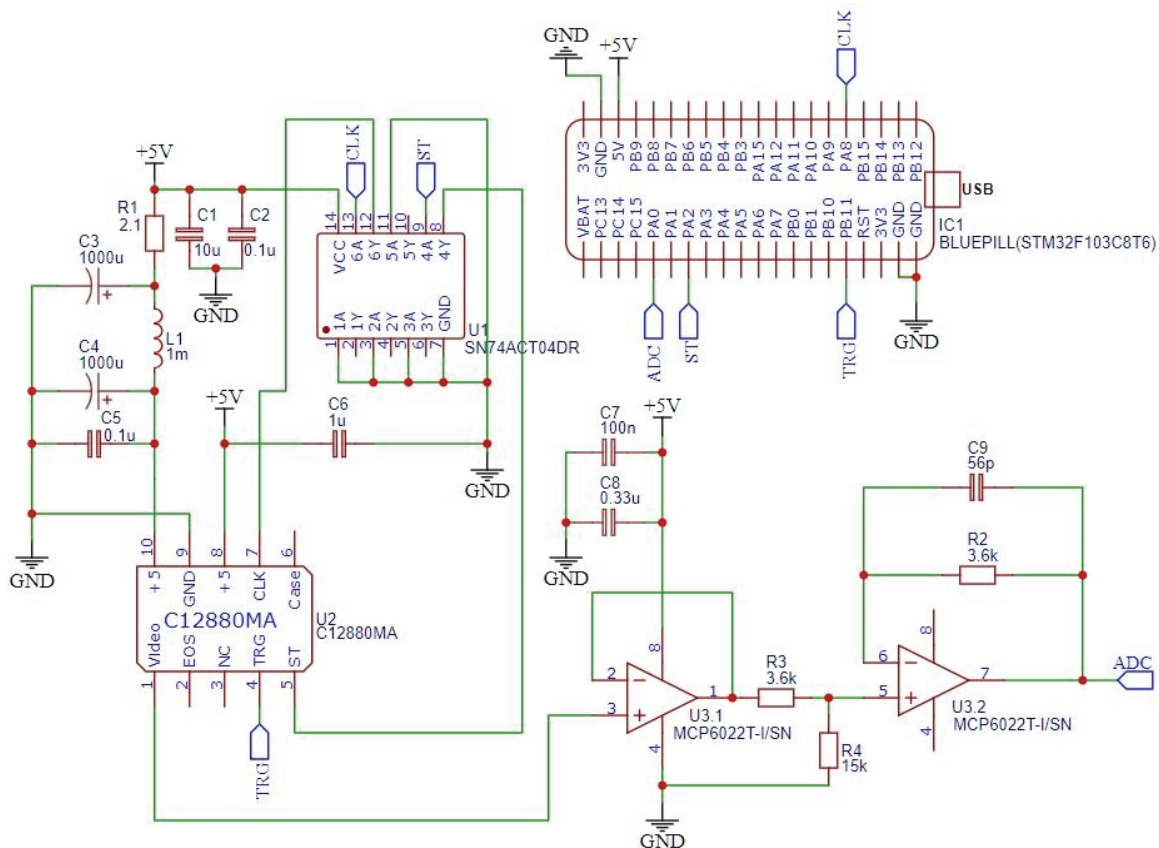
b

Figure 1 – Connection diagram of mini-spectrometrs Hamamatsu C12880MA (*a*) and C11708MA (*b*) to the microprocessor board ARM STM32F103C8T6 STM32

The mini-spectrometer is powered from the +5 V bus of the computer's USB port. The peak values of parasitic pickups on this bus can exceed several tens of millivolts, which can lead to the formation of noticeable interference at the Video output of these mini-spectrometers. Therefore, the LC Π-shaped filter is used to filter out the pickups that are inherent to this bus. Therefore, a low-pass LC filter is used to filter out the pickups that are inherent to this bus. The use of low-pass filtering makes it possible to reduce the level of these interferences to the level of the spectrometers' own noise.

The connection scheme of the C11708MA mini-spectrometer differs from that in Figure 1*a* by using a digital Gain signal, which allows increasing the sensitivity of the C11708MA by a factor of 3.5 when a high level is applied to pin 10. At the same time, the capacitor rating of the C11708MA

integration node is reduced from 4.8 to 1.4 pF [11]. Also the connection diagram of the C11708MA does not contain a resistive divider at the U3.1 output, because the range of the video signal of this mini-spectrometer is narrower, only from 0.15 to 3.3 V.

Software features

The widespread introduction of diffuse reflectance spectrophotometers is impossible without ensuring the ease of obtaining, storing, and processing the obtained spectra. Therefore, a mandatory requirement for the spectrophotometers under consideration is the ability to easily connect to modern portable computer equipment. For this purpose, the software created by the authors contains two levels. On the lower level, the STM32 firmware generates TTL signal diagrams that define the modes

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of operation of the mini spectrometer in use. It also provides frame reading, averaging and transmission via the USB bus to the upper level. The upper-level program is specially created on the basis of the powerful Matlab system of computer mathematics. Such a solution provides a quick modification of the applied software when solving spectro-photometric tasks in different branches of science and technology.

The firmware provides continuous control of the mini-spectrometer by commands of the control computer, which are received via the USB bus. A special cascade mode of STM32 timers is used, which ensures the formation of stable time diagrams of the generated TTL signals. In this mode, some timers hardware control start, clocking and dynamic changes in the parameters of other timers, ADCs and STM32 output port states. Therefore, before starting the process of obtaining a frame you only need to set the necessary parameters of the four timers, the ADC and DMA direct memory access block. The program is no longer involved in clocking, setting the exposure time and reading the frame. The proposed solution provides stable operation of the mini-spectrometers in a wide range of frame exposure values from tens of microseconds to tens of seconds.

The top-level software provides the selection of the required measurement modes:

1) a single start with the possibility of accumulating a specified number of frames *n* for their further averaging;

2) continuous with the possibility of averaging the obtained spectra with the help of a sliding time window with the length of *n* frames.

The program contains an option for automatically selecting the exposure time or setting its required value. Formation of a scale of counts by wavelength λ_i (this scale is non-linear) and output of the received spectra on the screen is provided. Necessary dialog tools for saving the obtained measurement results to the computer memory in the form of a file are available. The saved file also contains the necessary measurement parameters. The program contains the option of smoothing the obtained spectra on the short-wave and long-wave wings of the spectrophotometer spectral range using the Savitsky–Holley filter. Such a solution significantly improves the visual perception of spectra with insufficient signal-to-noise ratio at the edges of the range. The program contains an option to switch to a linear wavelength scale with a smaller sampling interval, based on the interpolation of the resulting spectrum by cubic splines. The small size of the C12880MA and C11708MA spectrometers can lead to a shift in their wavelength readout scale λ_i, which is due to their aging process. Hamamatsu gives the corresponding polynomial coefficients in the data sheet of each spectrometer. Therefore, the program contains an option for determining the value of the arising shift $\Delta\lambda$ of the scale λ_i by the emission of the He-Ne laser.

Calibration procedure for spectrophotometers

Spectrometer manufacturers calibrate the wavelength scale. In this case the reference gasdischarge sources of radiation and interpolation of values in the intervals between the registered lines of the spectrum are used. The data sheets of the C12880MA and C11708MA minispectrometers contain the p_k coefficients of the 5-th degree polynomial. They are used in the calculation of the wavelengths λ_i which correspond to the indices of the *i*-th elements of the linear photodiode arrays $\lambda_i = \sum_{k=0}^{5} p_k i^k$. The spectrometers are not usually calibrated by the intensity of the registered radiation $I(\lambda)$. This calibration can be performed by the manufacturer at the request of the user as an option with an additional charge for this service.

Different optical measurement schemes can be used for photometric measurements of the reflection parameters of condensed media. The spectrometer must be supplemented with a lens when it is necessary to determine the spectral density of brightness of radiation $L(\lambda)$ of sufficiently distant objects. In this case, the entrance slit of the spectrometer is placed in the focal plane of the objective, as shown in Figure 2. It is important to make sure that the plane angle, which corresponds to the spatial angle of focus $\Omega = 2\pi[1-\cos(\alpha)]$, fits exactly within the numerical aperture of the NA spectrometer. The numerical aperture NA is defined as the sine of half of the flat angle at the apex of the collecting cone $NA = \sin(\Theta/2)$. It is $NA = 0.22$ for the considered spectrometers [10, 11]. The diameter of the exit pupil of the lens used, as shown in Figure 2, must be chosen from the condition that the angle corresponds to $2\arcsin(NA) \approx 26°$.

In cases when it is necessary to determine the spectral density of brightness of radiation of a small area of the controlled surface, the measurement scheme with a single magnification is often used. In these cases, the surface of the medium and the spectrometer are placed at distances $2f$ from

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the front and rear principal planes of the lens used, respectively, as shown by the dashed lines in Figure 2. Note that it is also necessary to observe

the conditions of agreement of the spatial angle Ω_{2f} with the aperture NA of the spectrometer when using this measurement scheme.
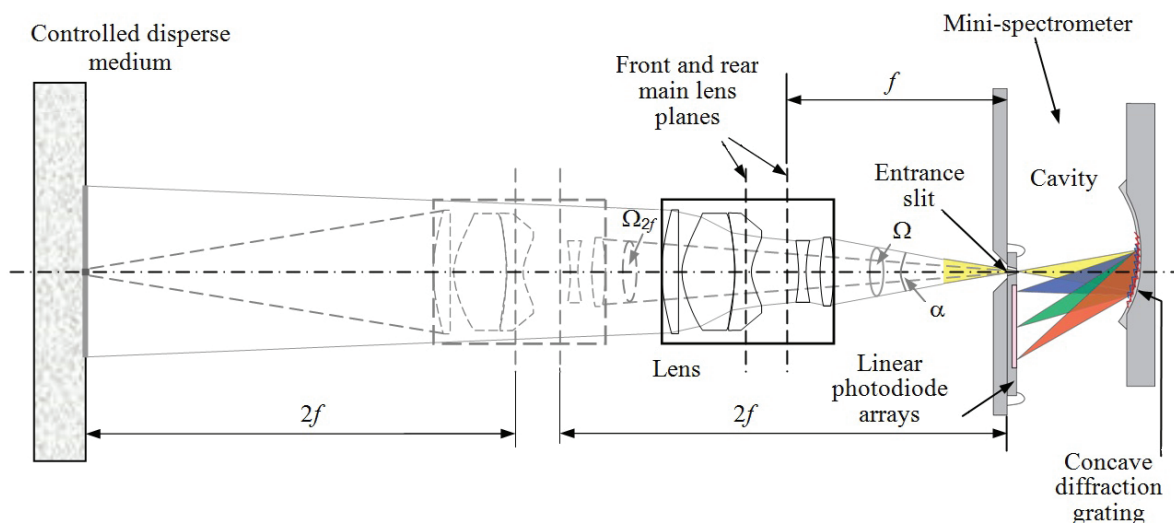
Figure 2 – Optical Scheme of photometry when focusing the lens to infinity (the lens is shown by solid lines) and at a single image magnification (dashed lines)

In cases where the calibration of spectrophotometers is performed by the user himself [12, 13], it is necessary to use standard light sources. The highest accuracy in reproducing the spectral density of surface luminosity $M(\lambda)$ at a given temperature T is provided by the models of black bodies (BB). Other reference emitters with simplified designs, such as a tungsten reference lamp strip, can be used in the absence of a BB. Spectral coefficient of thermal radiation of tungsten $\varepsilon_W(\lambda, T)$ accurately measured. This allows us to calculate its surface spectral luminosity $M_W(\lambda, T)$ quite accurately. The $M_W(\lambda, T)$ dependence is calibrated by the current I through the tungsten strip of the lamp by comparing its luminosity with the spectral luminosity density of the BB, denoted as $M_{BB}(\lambda)$. The spectral illuminance density of the slit $E(\lambda)$ can be accurately reproduced by projecting the image of the tungsten lamp strip onto the entrance slit of the spectrometer. It is necessary to project an image of the section of the lamp ribbon that has the maximum temperature. This makes it possible to determine the spectral dependence of $E(\lambda, T)$ by setting the necessary values of the spectral luminosity density $M_W(\lambda, T)$ of the tungsten strip.

When calculating it is necessary to take into account that the radiation of the tungsten strip in the direction normal to its surface is close to the radiation of the Lambertian emitters, i. e. the brightness of the strip's radiation $L_{rs} = M_{rs}/\pi$. Then the relation-

ship between the spectral luminosity density $E(\lambda)$ of the reference incandescent lamp strip image and the spectral luminosity density $M_{rs}(\lambda)$ of the strip itself is defined by the expression [14, p. 75]:

$$E(\lambda) = \frac{M_{rs}(\lambda)}{\pi} \frac{(1 - f/z)^2}{f^2} \frac{\pi D_l^2}{4} =$$

$$= \tau_l \frac{D_l^2}{4f^2} \left(1 - \frac{f}{z}\right)^2 M_{rs}(\lambda) = \tau_l K M_{rs}(\lambda),$$

where $K = \left(D_l^2/4f^2\right)\left(1 - f/z\right)^2$ is the dimensionless coupling coefficient between the illuminance of the strip image and the luminosity of the tungsten strip; τ_l, D_l and f is transmission, diameter and focal length of the lens used; z is distance from the surface of the reference source to the front main plane of the spectrophotometer objective lens.

The optical scheme with single magnification is the most convenient when calibrating the spectrophotometer by the reference tungsten incandescent lamp, because the size of the area of maximum heating of the lamp strip is small. When using this scheme, the expression for determining the average rate $\overline{V}(\lambda_i)$ (it is proportional to the photocurrents formed in the photosensitive elements of the linear of photodiodes array) of the rise of digital counts $\overline{D}_i(\lambda_i)$, which are formed by the i-th photosensitive elements of the linear array of the spectrometer, has the form:

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$$\bar{V}\left(\lambda_i,T\right)=\frac{\bar{D}_i\left(\lambda_i,T,\tau\right)}{\tau}=\frac{k_iKk_{QD}\left[i_{ph}\left(\lambda_i\right)+i_d\right]\tau}{\tau}=k_iKk_{QD}\left[\frac{es_{el}}{hc}\beta\left(\lambda_i\right)\eta\left(\lambda_i\right)\tau_{wL}\varepsilon_W\left(\lambda_i,T\right)M_{BB}\left(\lambda_i,T\right)\lambda_i\Delta\lambda_i+i_d\right]=$$

$$=k_iKk_{QD}\left[\frac{es_{el}}{hc}\beta\left(\lambda_i\right)\eta\left(\lambda_i\right)\tau_{wL}\varepsilon_W\left(\lambda_i,T\right)\frac{c_1}{\lambda_i^4}\left(e^{\frac{c_2}{\lambda_iT}}-1\right)^{-1}\Delta\lambda_i+i_d\right], \quad (1)$$

where λ_i is the wavelength of the registered radiation corresponding to the i-th element of the linear photodiodes array of spectrophotometer; k_i is a coefficient describing the heterogeneity in the sensitivity of the elements of the linear of photodetectors array, which is on average equal to one with a relative standard deviation of about a few percent; T is the temperature of the area of maximum heating of the tungsten strip of the lamp on the Kelvin scale; τ is frame exposure time; k_{QD} is the conversion coefficient of charges Q_i accumulated in the photosensitive elements of the linear of photodetectors array into digital readouts D_i; e, h and c are the electron charge, Planck's constant and the speed of light, respectively; c_1 and c_2 are the first and second radiation constants, respectively; s_{el} is the area of the photosensitive element of the linear of photodetectors array; $\beta(\lambda_i)$ is spectral dependence of the blaze angle of the diffraction grating used in the spectrophotometer; $\eta(\lambda_i)$ is spectral dependence of the quantum efficiency of the elements of linear photodetectors array; $\Delta\lambda_i$ is the width of the elementary segment of the spectrum, falling on one element of the linear of photodetectors array; $K=\tau_l(D_l/4f)^2$ is the relationship coefficient between the illumination of the ruler elements and the luminosity of the tungsten ribbon at $z=2f$; τ_{wL} is the transmittance coefficient of the sapphire window of the lamp; $i_{ph}(\lambda_i)$ is the photogenerated current produced by the i-th photodiode of the linear of photodetectors array; i_d is the average dark current of elements of the linear photodiode array.

The influence of the dark current can be neglected when using the operation of determining the average i_d current, which is then subtracted.

During calibration determine the absolute spectral sensitivity of the spectrophotometer by the brightness of radiation $S_L(\lambda_i)$. This makes it possible to recalculate the spectral dependence $V_i(\lambda_i)$ registered by the spectrophotometer into the spectral density brightness of radiation:

Calculations of the dependence using (1)

$$L\left(\lambda_i\right)=\frac{V\left(\lambda_i\right)}{S_L\left(\lambda_i\right)}.$$

will be approximate, due to the inevitable scatter of the spectral characteristics of the spectrometer elements. Therefore, the determination of $S_L(\lambda_i)$ should be performed by calibrating spectrophotometers using a reference emitter [13]. When using a reference tungsten lamp and $z=2f$, the expression applies:

$$S_L\left(\lambda_i\right)=\frac{\bar{V}_W^*\left(\lambda_i,T\right)}{L_W\left(\lambda_i,T\right)}=\frac{\pi\bar{D}_W^*\left(\lambda_i,T,\tau_{cal}\right)/\tau_{cal}}{\tau_{wL}\varepsilon_W\left(\lambda_i,T\right)\left(c_1/\lambda_i^5\right)\left(e^{c_2/\lambda_iT}-1\right)^{-1}}, \quad (2)$$

where $\bar{D}_W^*\left(\lambda_i,T,\tau_{cal}\right)$ and $\bar{V}_W^*\left(\lambda_i,T\right)$ are digital signals recorded during calibration with the frame exposure time τ_{cal} and the rate of their rise, respectively. When applying expression (2), it is convenient to use the dimensionality of the absolute spectral sensitivity $S_L(\lambda_i)$, equal to $(cm^2 \cdot sr \cdot \mu m)/(W \cdot ms)$, so we usually determine $L(\lambda_i)$ with dimensionality in $W/(cm^2 \cdot sr \cdot \mu m)$.

The lens in some applications of diffuse reflectance spectroscopy with spatial resolution can be not used, because the spectrometer collects the reflected radiation from the medium within its numerical aperture. During calibration, when calculating $S_L(\lambda_i)$ in these cases, it is necessary to divide the spectral luminosity of the tungsten in expression (2) by the lens transmittance τ_l.

In many cases of photometry it is necessary to use a field of view of the spectrometer with a weak divergence. Such a measurement scheme, as can be seen in Figure 2, is formed by placing the spectrometer slit in the focal plane of the lens. In this case the linear field of view of the spectrometer is increased and the calibration should be carried out according to the spectral density of brightness radiation of the BB model $L_{BB}(\lambda_i,T)$. Moreover, it is necessary to make sure that the spectrophotometer's field of view fits into the output aperture of the BB model. In this case, the expression for calculating $S_L(\lambda_i)$ is simplified:

$$S_L\left(\lambda_i\right)=\frac{\bar{V}_W^*\left(\lambda_i,T\right)}{L_{BB}\left(\lambda_i,T\right)}=\frac{\pi\bar{D}_W^*\left(\lambda_i,T,\tau_{cal}\right)/\tau_{cal}}{\left(c_1/\lambda_i^5\right)\left(e^{c_2/\lambda_iT}-1\right)^{-1}}.$$

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It should be remembered that the temperature of the emitting core of the BB must be more than 1500 ºC for the calculated $S_L(\lambda_i)$ values in the short-wave region of the spectrum to have a good signal-to-noise ratio. In this case we have to use a neutral attenuating filter with a known spectral transmittance $\tau_{NF}(\lambda_i)$, the attenuation of which must be taken into account when calculating $S_L(\lambda_i)$.

Main parameters, characteristics and examples of applications

The developed spectrophotometers with microprocessor board are 72 mm long and 40 mm wide when assembled without a lens. Therefore, they can be packaged in a cylindrical body with a C-Mount external lens mount. The compact lens "Basler Lens C23-3520-2M F2.0 f35 mm 2/3" with focal length $f = 35$ mm and $f/D = 2.0$ ratio was used for performance measurements of the developed spectrophotometers. This lens has a diameter of 35 mm and a length of 43.7 mm. In this case, the angle α at the apex of the assembled radiation cone of the tungsten tape of the reference lamp is not less than 2arcsin(NA), as shown in Figure 2.

Before calibrating the spectrophotometers based on the C12880MA and C11708MA, the offset of their wavelength readout scales λ_i was checked. As a reference monochromatic radiation source the HeNe laser LHN-303 with a wavelength of generation $\lambda = 632.819$ nm and the relative stability of the generation frequency not worse than 10^{-8} was used. The resulting readout scale offsets were small and were $\Delta\lambda = -3.4$ nm for C12880MA and $\Delta\lambda = -2.4$ nm for C11708MA. They were entered into the spectrophotometer software to shift the scales λ_i to the right by the corresponding value $\Delta\lambda$. The spectral range of operation of C12880MA was 307.8–878.2 nm, and that of C11708MA was 583.6 to 1086.5 nm. The spectral resolving power of spectrophotometers was determined by the standard technique at the half-height of the hardware function, i. e., the spectrum of diffusely scattered radiation of the LHN-303 laser. For C12880MA it was about 10 nm, for C11708MA it was about 15 nm.

The scheme of the setup used to calibrate the created spectrophotometers corresponded to the scheme shown in Figure 2. The distance between the rear main plane of the lens and the slit of the spectrophotometer, was $2f$, i. e. 70 mm. A neutral attenuation filter with a transmittance factor $\tau_{NF} = 0.0033$ was used to attenuate the illumination of the spectrophotometer slit, which is formed by projecting the image of a glowing tungsten strip of the LI10-300 lamp onto it. The absolute spectral sensitivities of the spectrophotometers that were obtained using (2) are shown in Figure 3.
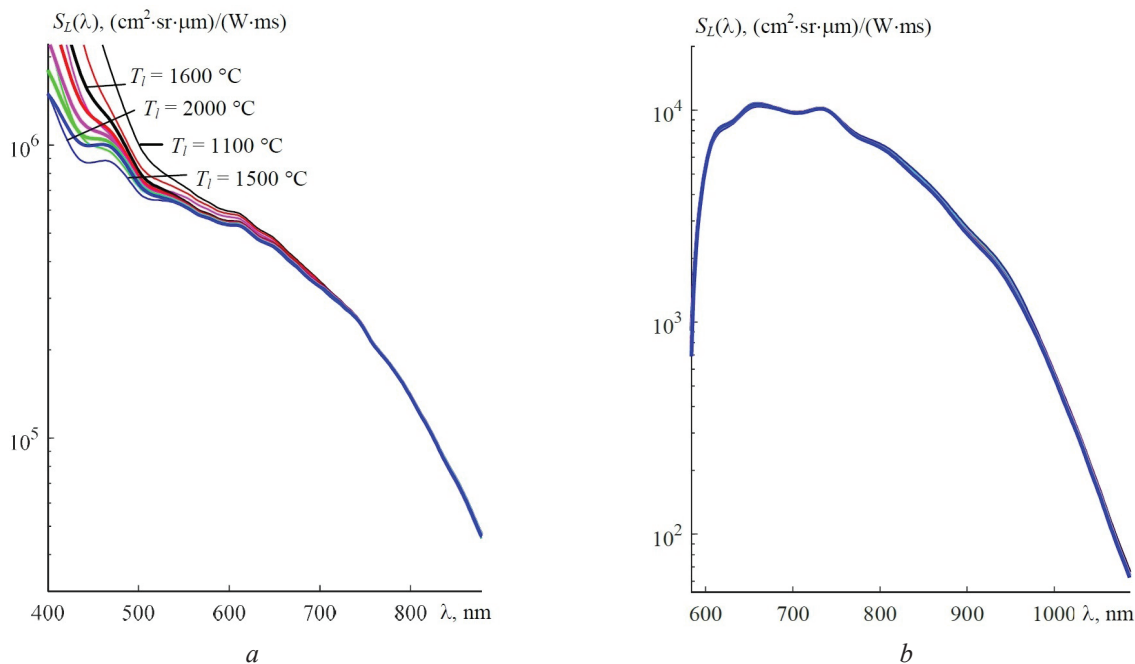
Figure 3 – Absolute spectral sensitivities of spectrophotometers based on C12880MA (*a*) and C11708MA (*b*), which are calculated from the emission of a reference SI10-300 tungsten lamp at ten different temperatures were shown in Figure 4

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An unpleasant feature of the C12880MA mini-spectrometer was revealed during the calibration work. This is a noticeable addition of radiation, which is scattered by the concave diffraction grating in the zero order of diffraction, to the spectrum recorded in the short-wave part of the spectrum. Many spectrophotometers based on concave diffraction gratings and photodetector arrays have this disadvantage. The C12880MA mini-spectrometer is small, so this effect is much stronger. The dependences shown in Figure 4*a* convincingly illustrate the effect of scattered radiation on the recorded spectra. Therefore, it should be taken into account that the spectra recorded by the C12880MA can be markedly distorted in the short-wave part of the range due to the contribution of powerful spectral components from the longer wavelength part of the spectrum. The spectrophotometer based on C11708MA has practically no marked distortions in the short-wave part of its spectral range. This effect, as follows from Figure 4*b*, appears only near the short-wave boun-dary, i. e. around 584 nm.
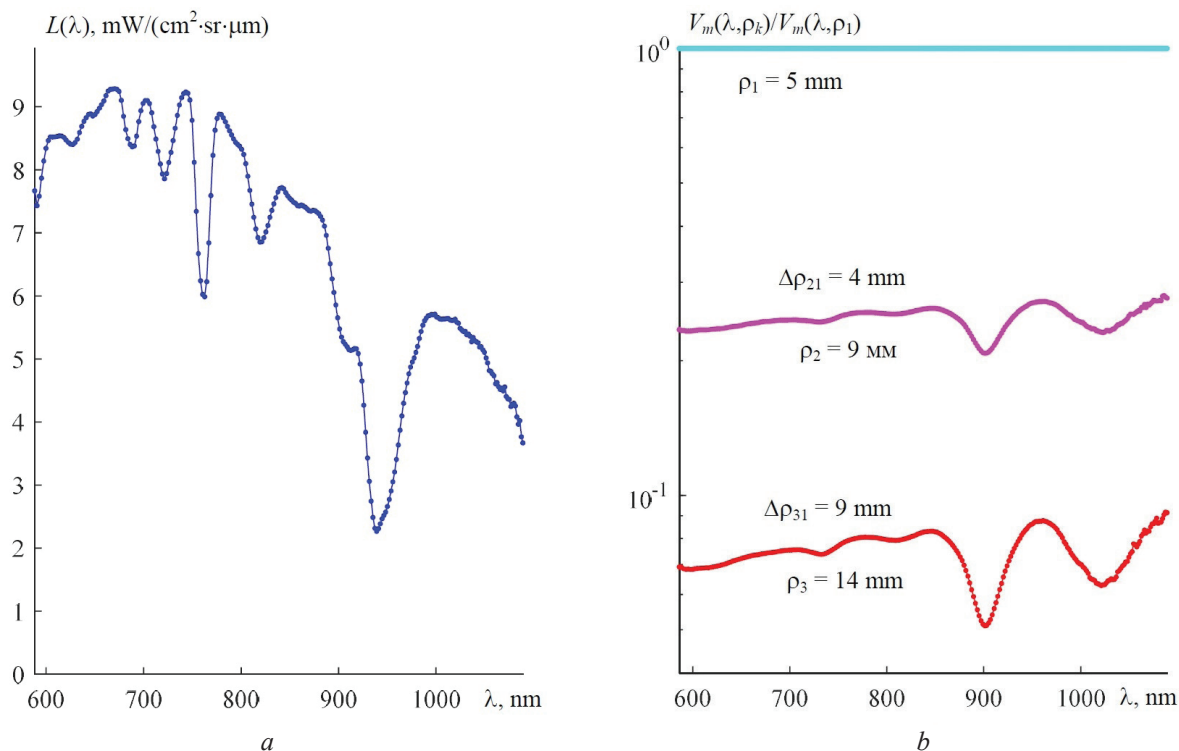
The experimentally measured $L_m(\lambda)$ dependences, shown in Figure 4 as solid lines, were determined using the spectral sensitivities of spectrophotometers $S_L(\lambda_i, T_l)$, which were obtained from the radiation of tungsten strip with brightness temperature T_l = 2000 ºC. The dependences of the spectral brightness density $L_m(\lambda)$, which were measured with a spectrophotometer based on C11708MA, turn out to be close to the calculated dependences. Small deviations of $L_m(\lambda)$ values in the long-wave part of the spectral range are caused by an error in determining the spectral transmit-tance of the attenuating neutral filter $\tau_{NF}(\lambda_i)$ in the infrared range. The influence of the effect noted above on the spectrum, which is formed at $\lambda < 480$ nm, we found it even in a high-quality fiber-optic spectrometer AvaSpec 2048WL (Holland) [13]. This disadvantage of spectrometers based on concave diffraction gratings and photodetector arrays must necessarily be taken into account when analyzing diffuse reflectance spectra in the short-wave region of the visible spectrum.
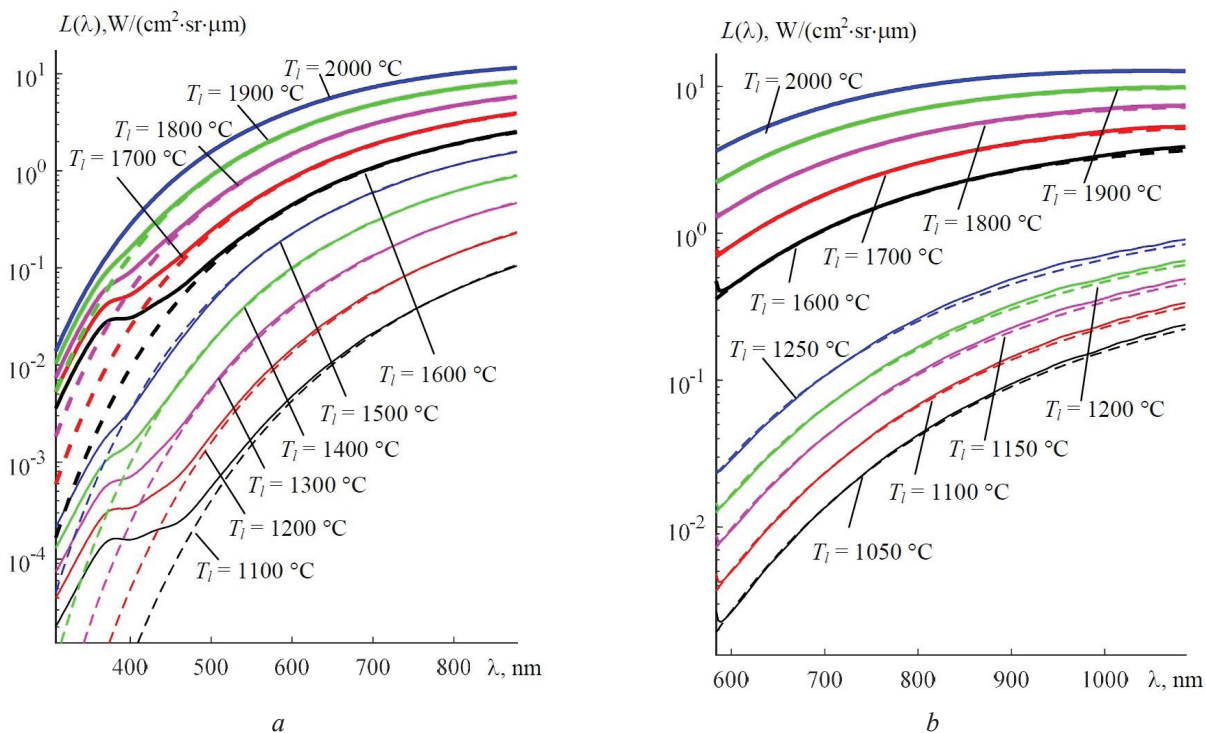
Figure 4 – The calculated spectral brightness $L(\lambda)$ of the tungsten ribbon strip radiation at different brightness temperatures T_l (dashed lines) and spectral dependences measured with the C12880MA (*a*) and C11708MA (*b*) spectrophotometers (solid lines)

Figure 5*a* shows the spectral brightness density of the diffuse reflection of a white sheet illuminated by the Sun. The Earth's atmosphere has a noticeable influence on the spectrum

of the illuminating radiation, for example, the absorption bands of O_2 with a maximum at $\lambda = 760$ nm and water vapor around 933–960 nm are clearly visible.

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Figure 5 – Spectral brightness $L(\lambda)$ of a sheet of white paper that is illuminated by the sun (*a*), and normalized spectral dependences for plastic Gehr-Pom-C by different distances ρ_k between the input point of the halogen lamp radiation through the optical fiber and the registration point (*b*), which were obtained by a spectrophotometer based on C11708MA

The normed diffuse reflectance spectra of the Gehr-Pom-C matte white plastic, which were obtained using a C11708MA-based spectrophotometer, are shown in Figure 5b. The normalization was carried out by dividing the spectra $V_m(\lambda_i, \rho_k)$ by the spectrum $V_m(\lambda_i, \rho_1)$, which was obtained at a minimum distance of $\rho_1 = 5$ mm between the point of radiation input into the plastic and the point of registration. The halogen lamp emission spectrum and spectrometer characteristics do not affect the ratio $V_m(\lambda_i, \rho_k)/V_m(\lambda_i, \rho_1)$ with this normalization. The obtained normalized spectral dependences coincide with similar dependences that were obtained using a spectrophotometer based on the AvaSpec 2048WL spectrometer. It can be clearly seen that the white matte Gehr-Pom-C plastic has radiation absorption bands, which appear stronger with increasing distance ρ between the radiation input point and the registration point.

Conclusion

Progress made in the production of miniature spectrometers and microprocessors opens up the possibility of using the C12880MA and C11708MA

in inexpensive spectral techniques, which are designed to control the diffuse reflectance spectra of various materials and media in the visible and near-infrared spectrum ranges. Studies of the characteristics of portable spectrophotometers based on Hamamatsu mini-spectrometers and STM32 microprocessors indicate the prospects for their use in controlling difuse scattering spectra of condensed finely dispersed mediums.

The described graduation method allows you to identify the range of the spectrum, in which its distortion due to the scattering of radiation into the zero order of diffraction of the concave diffraction grating, can not be taken into account.

The conducted studies point to the promising development of inexpensive computerized portable diffuse reflectance spectroscopy techniques with spatial resolution, which can be widely used in various sectors of science and industry.

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