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OPTOELECTRONIC THREE-WAVE MOISTURE METER OF RAW COTTON

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Abstract: The article provides information on the development of a tricolor LED emitter of the middle infrared region of the spectrum, consisting of a measuring LED chip for fibers with a wavelength of 1.8 microns, a measuring LED chip for water with a wavelength of 1.94 microns and a reference LED chip with a wavelength of 2.2 microns, as well as an optoelectronic three-wave moisture meter raw cotton developed on the basis of this tricolor LED emitter. To improve the accuracy of measuring the moisture content of raw cotton, an optoelectronic three-wave moisture meter has been developed, the presence of three radiation channels allows not only simultaneously monitoring the optical absorption of water and the physicochemical properties of cotton fibers. The moisture meter consists of an exponential voltage shaper, three emitting diodes (emitting at reference, measuring wavelengths and at a wavelength lying in the absorption band of uninformative parameters), a controlled object, a photodetector and a photoelectric signal processing unit. Characteristic features of the optoelectronic three-wave moisture meter are high selectivity, sensitivity, and measurement accuracy. In order to exclude the influence of temperature on the measurement result and, consequently, increase sensitivity, a three-wave structural diagram was used. An automated system for monitoring and controlling the storage of raw cotton on bunts based on a three-wave moisture meter has been developed.

Keywords: cotton - raw material, humidity control, water absorption spectra, optoelectronics, LED, photodiode, moisture meter, sensitivity, accuracy, control, automation, mechatronics.

Introduction. Currently, electromagnetic oscillations in the optical wavelength range are being intensively used in technology. The development of optoelectronics has led to remarkable changes in our daily lives [1]. Today, optoelectronic devices are widely used in many areas of human activity [2].

The development of optoelectronic devices is one of the most important tasks in instrumentation engineering. It enables the acquisition, transmission, and processing of information across all regions of the optical spectrum by converting optical signals into electrical ones. It also allows for the automation of control over various objects and technological processes. The rapid advancement of optoelectronic components and their latest achievements opens up vast opportunities for solving practical problems of significant economic importance.

Based on the photoelectric detection method, various optoelectronic non-destructive testing devices can be created. These typically consist of a light emitter and a photodetector arranged in a specific manner relative to the object under inspection [3]. The essence of converting a monitored parameter into a photoelectric signal lies in the fact that the object is illuminated by a radiation beam with a specific spectral composition. A portion of the radiation, after interacting with the object, is received and converted into a photoelectric signal.

A whole range of optoelectronic sensors has been developed based on spectrally matched LED-photodiode pairs: a paper moisture analyzer, carbon dioxide and methane detectors, a water content analyzer in oil, and a new type of hydrogen sensor based on the photoelectric registration method [4–7].

Optoelectronic devices do not generate electromagnetic interference and are not affected by such fields, which creates favorable conditions for the study and development of optoelectronic methods and devices [8].

Research Methodology. Among the parameters for monitoring and controlling technological processes, one of the most important is humidity [9]. For example, the moisture content of raw cotton is determined both before harvesting and during technological processing. During atomic polarization, the oxygen atoms that are part of water molecules perform complex movements, which result from the synthesis of three standard oscillations: totally symmetric angular, totally symmetric stretching, and asymmetric stretching vibrations. The absorption bands of these oscillations correspond to 2.74; 6.7; and 2.66 μm, respectively. The absorption coefficients at these wavelengths are quite high; however, due to the lack of stable light-emitting diodes and detectors in the mid-infrared (IR) range, these wavelengths are not used in the development of industrial devices. The mid-infrared range is of greatest interest. As shown in Table 1, the water absorption spectrum in the mid-IR region consists of higher harmonics and combination bands of the standard oscillations [10]. The most optimal wavelength for practical use is 1.94 μm. Since water absorption in this range is due to induced polarization accompanying atomic vibrations, this phenomenon is considered atomic polarization. When water is absorbed by a substance, it alters its spectrum. A comparison of the spectral characteristics of dry matter and the same substance with 9% H_2O moisture content shows that at the wavelength of 1.94 μm, water exhibits significant absorption [11].

Table 1. Absorption spectra of water.

Wave length (μm)	Assignment	Absorption coefficient (%)
0,76	Higher harmonics	0.26
0,97	The same	0.46
1,19	Combination components	1.05
1,45	The same	26.0
1,94	The same	100

Therefore, if the controlled object is exposed to infrared (IR) radiation with a specific wavelength and the power of the transmitted or reflected radiation flow is measured, it will vary depending on the humidity.

However, when measurements are taken at only one wavelength, errors may occur. The main sources of these errors, apart from humidity, include scattering of the radiation by the measured substance, its thickness, and so on. To eliminate these errors, an additional radiation flow with a reference wavelength that lies outside the absorption band of water is used.

The wavelengths of the measuring and reference beams can be optimally selected based on the spectrum of the measured substance, the humidity measurement range, and other requirements. When designing optoelectronic devices using semiconductor emitters, spectral characteristics are the basis for selecting the wavelengths of the measuring and reference radiation beams.

In addition to fluctuations in the LED's radiation power, the sensitivity of the photodetector, and the quality of the fabric surface, the reflection coefficient of the reference wave can also be influenced by the physicochemical properties of the fibers. Changes in these properties can therefore introduce additional error into the humidity measurement results.

Three-color led emitter for humidity control

The key element of the three-color LED module is the LED heterostructures based on narrow-bandgap semiconductor materials of the A^3B^5 group. The emission wavelength of the LED is determined by the bandgap width, i.e., by the composition of the solid solution in the active region. For an LED with an emission peak at 1650 nm, a quaternary solid solution of AlGaAsSb with 3% aluminum content is used in the active region. For an LED with an emission peak at 1940 nm, a quaternary solid solution of GaInAsSb with 9% indium content is used in the active region. For an LED with an emission peak at 2200 nm, a quaternary solid solution of GaInAsSb with 19% indium content is used in the active region. In all cases, a wide-bandgap solid solution of AlGaAsSb with 64% aluminum content is used as an electron confinement layer. The structures are grown on GaSb substrates using Liquid Phase Epitaxy (LPE) or Metal-Organic Chemical Vapor Deposition (MOCVD) [12].

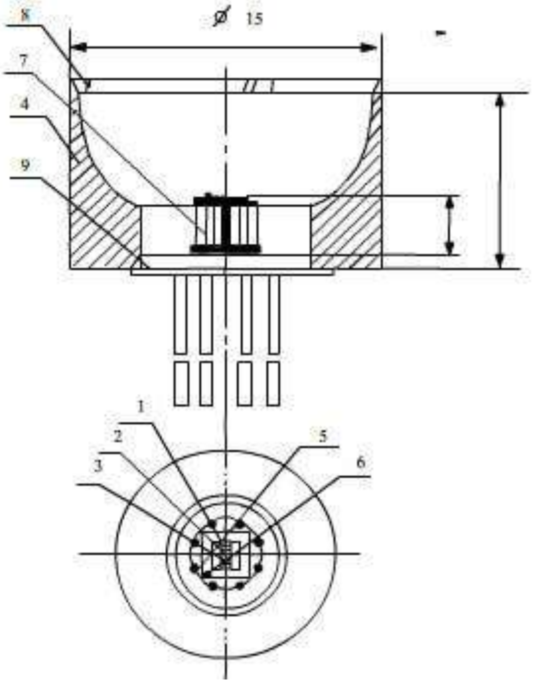


Figure 1. Three-color LED for humidity control

The tricolor LED includes:

1. Measuring LED chip for fiber – LED 16
2. Measuring LED chip for water – LED 19
3. Reference LED chip – LED 22
4. Parabolic reflector
5. Ceramic substrates
6. Temperature sensor
7. Thermoelectric cooler (Peltier element)
8. Quartz glass
9. TO-39 package

LED chips ranging in size from 0.3×0.3 mm to 1.0×1.0 mm are formed from heterostructures using photolithography. Then, the chip is mounted on a ceramic or silicon substrate with dimensions ranging from 0.8×0.8 mm to 2.0×2.0 mm. A three-color LED for monitoring the moisture content of raw cotton is shown in Fig. 1."

The module is mounted in a standard TO-39 package with leads (9). The built-in thermoelectric cooler (Peltier element) with a size of 3×3 mm (7) ensures a temperature difference between the hot and cold ends of at least 60 degrees without load. A temperature sensor (6) is glued to the cold side of the thermoelectric cooler.

Three pre-mounted LED chips on substrates, emitting at wavelengths of 1650 nm (LED 16), 1940 nm (LED 19), and 2200 nm (LED 22) (1, 2, and 3), are attached to the open surface of the cold end of the thermoelectric cooler. The anodes and cathodes of the LEDs are connected by gold wires to four external terminals (pins 1–3, 6) of the TO-39 package (see Fig. 1). The terminals of the thermoelectric cooler and the temperature sensor are connected to external terminals 4, 5, 7, and 8 of the TO-39 package. A parabolic reflector with a 15 mm diameter window is welded to the housing to narrow the radiation pattern. Figure 2 shows the spectral characteristics of the tricolor LED emitter and the photodetector.

This tricolor LED emitter with a built-in thermoelectric cooler, designed for the mid-infrared (mid-IR) spectral range, is characterized by its compactness and structural integration.

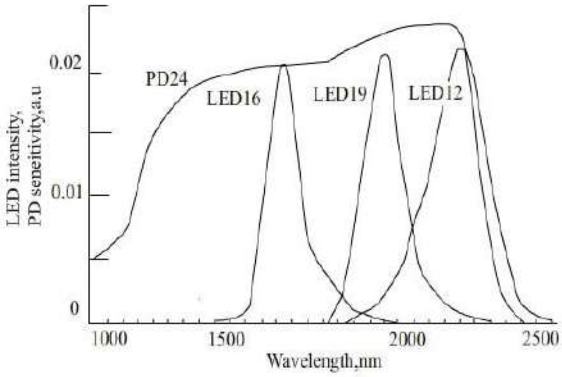


Fig. 2. Spectral characteristics of the three-color LED emitter (LED 16, LED 19, LED 12) and the photodetector (PD 12) for humidity control

The housing contains three different LED emitters (two measurement channels and one reference), a thermoelectric cooler, and a thermistor. The small distance between the chips ensures identical operating conditions for the three channels, which is a significant advantage of this design compared to conventional three-channel configurations. The LED lifespan of 80,000 to 100,000 hours significantly exceeds that of other types of IR radiation sources.

The well-known process of slow power degradation in semiconductor LEDs occurs equally in three identical chip structures, ensuring the stability of the differential signal over a period of 8–10 years. The design allows for selecting a common temperature for the three emitters within the range of -10 to +20°C and maintaining it consistently with minimal power consumption. The small size and high efficiency of the thermoelectric cooler make it possible to maintain a temperature close to room level at a constant current of about 10 mA.

Results. Optoelectronic Three-Wavelength Moisture Meter.

Based on the photoelectric registration method, various optoelectronic non-destructive testing devices can be developed, consisting of an emitter and a photodetector arranged in a specific way relative to the object under inspection.

Single-wavelength optoelectronic devices are used to determine the qualitative and quantitative parameters of solid substances and materials (such as density or mass) or to analyze the optical properties of liquids and gases. They usually consist of one LED and one photodiode. The LED emits at a specific wavelength corresponding to the absorption band of the studied substance. The photodiode, with a corresponding spectral sensitivity, detects the radiation and generates an output electrical signal. The design of a single-wavelength optoelectronic device is simple, but it has several drawbacks, the main one being the dependence of the measurement result on the properties of the material under inspection.

Two-wavelength optoelectronic devices help eliminate factors such as the influence of non-informative parameters of the object. If the monitored medium is multicomponent (e.g., when measuring the moisture of raw cotton), an additional reference wavelength is introduced to eliminate the influence of different components of the medium [13].

To improve the accuracy of raw cotton moisture measurement, we have developed an optoelectronic three-wavelength moisture meter. The presence of three radiation channels allows not only for the simultaneous monitoring of the optical absorption of water but also for the physicochemical properties of cotton fibers.

A tricolor LED module with a built-in thermoelectric cooler for the mid-IR range meets the requirements of portable optical analysis.

Let us consider the three-wavelength scheme. If the object under inspection is irradiated with IR radiation F_0 at the reference $F_{0\lambda 1}$ nd measuring $F_{0\lambda 2}$ frequencies, then the radiation passing through the object will be, respectively:

$$F_{\lambda 1} = F_{0\lambda 1}\, exp(-k_1 m_1)$$
$$F_{\lambda 2} = F_{0\lambda 2}\, exp(-k_1 m_1 - k_2 m_2),$$

$$F_{\lambda 3} = F_{0\lambda 3}\, exp(-k_1 m_1 - k_2 m_3),$$

where **k_1, k_2, k_3** are the absorption coefficients at the reference and measurement wavelengths; **m_1, m_2, m_3** are the masses of the section of the controlled object and the moisture, respectively;

$F_0\lambda_1$ is the radiation flux at the reference wavelength, and **$F_0\lambda_2$, $F_0\lambda_3$** are the radiation fluxes at the measurement wavelengths incident on the controlled object; **$F\lambda_1$** is the radiation flux at the reference wavelength, and **$F\lambda_2$, $F\lambda_3$** are the radiation fluxes at the measurement wavelengths that have passed through the controlled object.

After initially aligning the flux values according to the photodetector's response, and taking into account the photocurrent value, we obtain:

$$I_{F1} = CU^{\gamma}[F_{0\lambda 1}\, exp(-k_1 m_1)]^{\alpha};\ I_{F2} = CU^{\gamma}[F_{0\lambda 2}\, exp(-k_1 m_1 - k_2 m_2)]^{\alpha},$$
$$I_{F3} = CU^{\gamma}[F_{0\lambda 3}\, exp(-k_1 m_1 - k_3 m_3)]^{\alpha},$$

where γ and α are nonlinearity indices; C is a constant coefficient; U is the supply voltage since a single photodetector powered by a single power source is used, we have

$$U_1 = A[F_{0\lambda 1}\, exp(-k_1 m_1)]^{\alpha};\ U_2 = A[F_{0\lambda 2}\, exp(-k_1 m_1 - k_2 m_2)]^{\alpha},$$
$$U_3 = A[F_{0\lambda 3}\, exp(-k_1 m_1 - k_3 m_3)]^{\alpha},$$

Where: $A = CU^{\gamma}R_h$; R_h — load resistor resistance.

To obtain a signal proportional to humidity, it is necessary to perform a division operation and take the logarithm. In this case:

$$\frac{U_2}{U_1} = \frac{[F_{0\lambda 2}\, exp(-k_1 m_1 - k_2 m_2)]^{\alpha}}{[F_{0\lambda 1}\, exp(-k_1 m_1)]^{\alpha}}$$

To obtain a signal proportional to the cotton fiber, it is necessary to perform a division operation and apply logarithmation.

$$\frac{U_3}{U_1} = \frac{[F_{0\lambda 3}\, exp(-k_1 m_1 - k_3 m_3)]^{\alpha}}{[F_{0\lambda 1}\, exp(-k_1 m_1)]^{\alpha}}$$

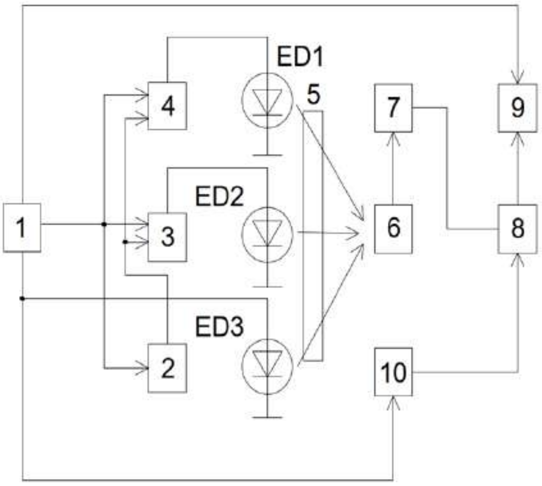


Fig. 3. Block diagram of the optoelectronic three-wavelength moisture meter

The optoelectronic three-wavelength moisture meter includes the following components:

1 - pulse generator; 2 - frequency divider; 3, 4 - exponential modulators, respectively; 5 - controlled object; 6- photodetector; 7, 10 - differentiating devices; 8 - coincidence circuit; 9 - pulse counter.

Figure 3 shows the block diagram of a three-wavelength moisture meter with two measurement channels. The moisture meter consists of an exponential voltage generator, three emitting diodes (emitting at the reference wavelength, the measurement wavelength, and a wavelength located in the absorption band of non-informative parameters), the monitored object, a photodetector, and a photoelectric signal processing unit. The use of a functional sweep in this case makes it possible to improve the accuracy and simplify the circuit of the moisture meter. Both reference signals are generated according to a decaying exponential law.

The moisture meter operates as follows.

The controlled material or product is irradiated by three light beams from LEDs: one at the measuring wavelength $\lambda_1 = 1.94$ μm, and two at reference wavelengths $\lambda_2 = 1.6$ μm and $\lambda_3 = 2.2$ μm, respectively.

The pulse generator (1) produces rectangular pulses. These pulses are fed to the inputs of the exponential modulators (3, 4) and to the input of the frequency divider (2), which synchronizes the start of exponential pulse formation and the filling pulses from the pulse generator. The formed current pulses pass through the LEDs and generate light beams at the three wavelengths. These beams interact with the controlled object and are then received by the photodetector (6). The signals from the output of the photodetector (6) are sent to the input of the first differentiating device (7). The differentiated signal from the output of the first differentiating device (7) is sent to one input of the coincidence circuit (8). The signal from the output of the second differentiating device (10) is sent to the other input of the coincidence circuit (8). At the output of the coincidence circuit (8), pulses appear from the beginning of the exponential signal until the phase shift of the photoelectric signal. The signal from the coincidence circuit is then fed to the pulse counter (9), and the readings of the counter determine the moisture content of the controlled object.

Thus, the obtained research results demonstrate the possibility of developing and constructing an optoelectronic three-wavelength moisture meter with enhanced sensitivity in any predefined narrow measurement range.

Automated control and management system for storing raw cotton in bales

An automated control and management system for storing raw cotton in bales has been developed, which integrates the following components into a single control unit: an optoelectronic three-wave raw cotton moisture meter. Figure 4 shows the block diagram of the automated control and management system for storing raw cotton in bales. The system consists of four moisture meters (1) connected into a unified control block, which are sequentially connected through a switch (2) to an optical emitter (3). This emitter is connected via a fiber-optic communication line (4) to a photodetector (5), which is in turn connected to a recorder (6) and a controller (7). One output of the controller is connected to a computer (8), and the other to a relay board (9), which includes four ventilation units (10) that function to extract hot air from the tunnels.

The automated control and management system for storing raw cotton in bales operates as follows: the moisture meters (1) monitor the moisture level inside the bales and transmit these signals through the switch (2) to the optical emitter (3), which converts the electrical signal from the moisture meters into optical radiation. This optical signal is transmitted through the fiber-optic communication line (4) to the photodetector (5), which converts it back into an electrical signal and sends it to the recorder (6), which then passes the signal to the controller (7). The controller (PLC110 logic controller by the Russian company "OVEN") operates based on the modern programming language "CodeSYS", and is managed by the computer (8). Signals are automatically sent through the relay board (9) to activate the ventilation units (10).

To prevent overheating of the cotton in the bales, a mechatronic device has been proposed. This device covers the rear part of the tunnel with a height of 2 meters and a width of 1 meter, as well as the sides of a metal pipe with a diameter of 273 mm, which is part of the hot air suction unit installed in the tunnels (Figure 5).

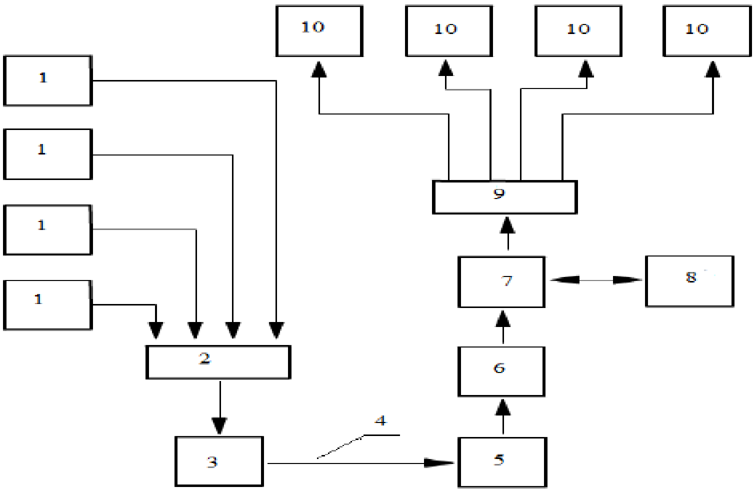


Fig. 4. Automated system for monitoring and controlling the storage of raw cotton in bales

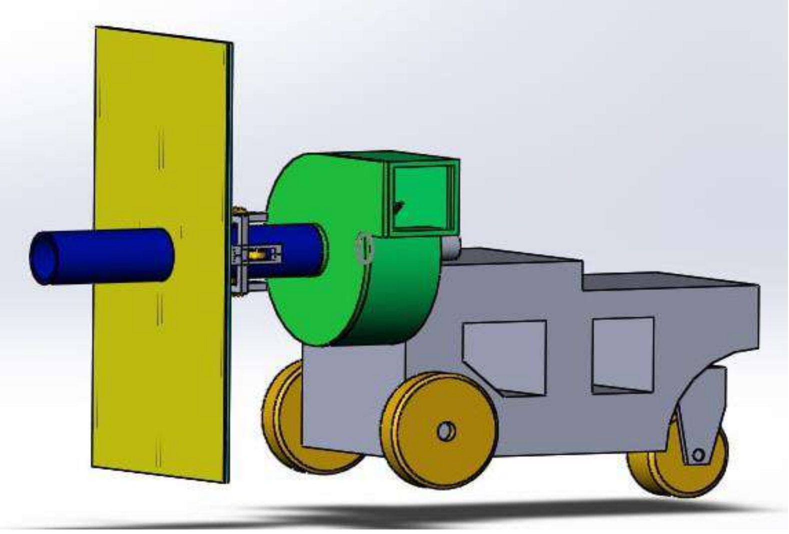
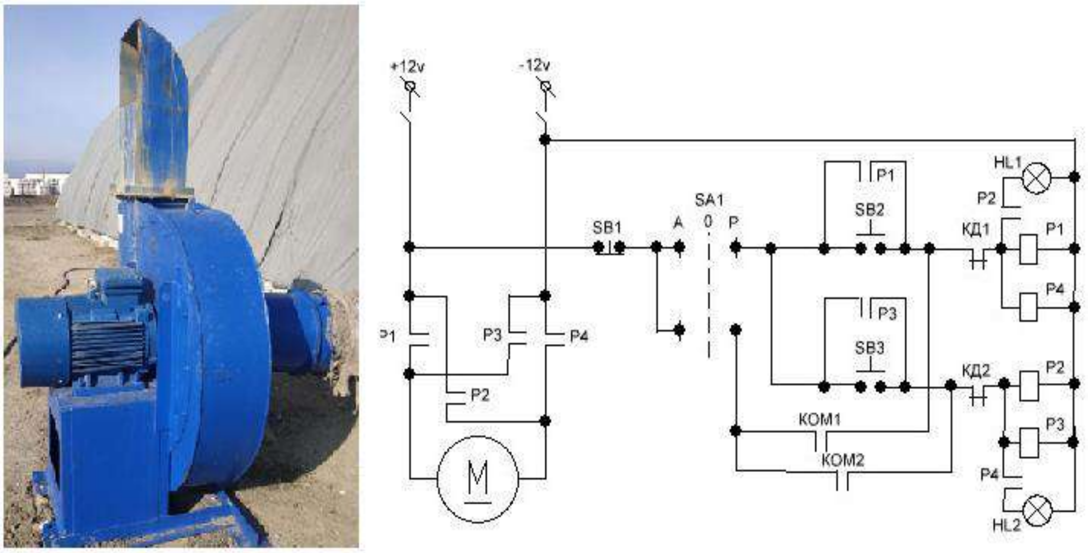


Fig. 5. Mechatronic device for automatic opening and closing of the cotton module tunnel



a) b)

Fig. 6.b. Ventilation device BL-UVP10M (a) and automatic control diagram (b)

Thus, it is possible to extract hot air from the tunnels over a specified period of time (6–8 hours) based on the set times (evening and morning) using the BL-UVP10M ventilation unit.

Conclusion. A three-color LED operating in the mid-infrared spectral range has been developed. It consists of a measuring LED chip for fibers with a wavelength of 1.8 μm, a measuring LED chip for water with a wavelength of 1.94 μm, and a reference LED chip with a wavelength of 2.2 μm. The LED design allows for setting a common temperature for the three emitters in the range of -10 to +20°C and maintaining it consistently with minimal electrical power consumption.

To improve the accuracy of raw cotton moisture measurement, an optoelectronic three-wavelength moisture meter has been developed. The presence of three emission channels enables simultaneous monitoring of both the optical absorption of water and the physical-chemical properties of cotton fibers. The moisture meter consists of an exponential voltage generator, three emitting diodes (emitting at reference, measuring wavelengths, and at a wavelength falling within the absorption band of non-informative parameters), the controlled object, a photodetector, and a photoelectric signal processing unit.

The key features of the optoelectronic three-wavelength moisture meter are high selectivity, sensitivity, and measurement accuracy. To eliminate the influence of temperature on the measurement result and thus increase sensitivity, a three-wavelength structural scheme was used.

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CONTENTS

TECHNICAL SCIENCES: COTTON, TEXTILE AND LIGHT INDUSTRY

TECHNICAL SCIENCES: AGRICULTURE AND FOOD TECHNOLOGIES

CHEMICAL SCIENCES

TECHNICAL SCIENCES: MECHANICS AND MECHANICAL ENGINEERING

ADVANCED PEDAGOGICAL TECHNOLOGIES IN EDUCATION

ECONOMICAL SCIENCES