Development of a personal portable dosimeter of an effective dose with the RFID data channel

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The aim of the work is development of a personal portable dosimeter of effective dose with the RFID data channel without built-in power supply source. Such personal dosimeters are in demand for long-term monitoring of the effective dose of ionizing radiation received by personnel when working with potentially hazardous radiation objects. The proposed X-ray detector has a novelty design with a Gafchromic EBT3 radiochromic film-based sensor element changing its transparency when exposed to ionizing radiation. The dosimeter circuit diagram has been developed and implemented. The dosimeter includes a microcontroller device estimating changes in the effective dose by determination of a degree of the sensor element varying transparency. The specific feature of the device is that it has no built-in power supply source. The dosimeter is supplied with radio frequency data transmission system. The active operating mode of the dosimeter is realized solely at the moments of data reading by external RF devices. The sensitivity of the developed device is expected to be at 0.034% / mGy, the lower dose limit of sensitivity is 1 mGy. The error of dose measuring by this method does not exceed 0.25 mGy.

Keywords: individual dosimeter, effective dose, radio frequency communication channel, radiochromic film

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Introduction

When performing works related to the risk of radiation exposure, the effective dose is an adverse effect risk measure [1]. Monitoring the dose of ionizing radiation received by personnel during work with potentially hazardous radiation objects is an integral part of the labor protection and life support system in the nuclear industry, food industry, in radiological medical institutions, Ministry of Emergency Situations, etc. In addition, such radiation monitoring is also in demand in the construction industry, as well as for tracking the state of the environment and its protection [2].

There are a large number of methods and instruments for monitoring the rate of ionizing radiation dose [3]. At the same time, monitoring the effective (cumulative) dose is performed either using thermoluminescent dosimeters or using indirect methods of converting the dose rate into the effective dose, which requires a number of technological operations with the use of special equipment. Unfortunately, modern personal miniature dosimeters, which directly display the effective dose, are not available in the Russian market. Thus, the development of a personal portable dosimeter, which allows measuring the effective dose for a long period and instantly transmits this information in a non-contact way is in demand and is an urgent task.

The small-size design is one of the most important requirements for such devices, which is due to the need to place the dosimeter on the body, clothing, or the packaging of products subjected to radiation. At the same time, in order to fulfill the small-size condition, it is necessary to solve a number of problems related to the study and selection of a material for dosimeter, which has to be sensitive to low doses, the study of methods for reading the effective dose information, the ability to use technology for non-contact transfer of information, the possibility of excluding a power source and organizing distributed networks for reading, transfer and storage of personal information on the accumulated dose in a single information system.

Compliance with these requirements is possible by creating a small-size personal portable dosimeter with a radio frequency communication channel, which is asynchronously connected to the information system for...
reading, transmitting and storing personal information on the absorbed dose by means of non-contact readers.

The operation of the proposed personal portable dosimeter is based on the effect of a change in the optical properties of the sensing element under the action of ionizing radiation. The sensing element in this case is made of radiochromic materials. For example, it may be a Gafchromic EBT3 radiochromic film [4, 5]. Ashland company manufactures a series of Gafchromic-branded films designed to register gamma and X-rays, electron beams, protons, ions, α-particles, and neutrons. The active component of the film consists of chips of sub-micronic radiation-sensitive monomer LiPCDA. The polymerization reaction is triggered by ionizing radiation, while the amount of polymer and the color change depth are proportional to the absorbed dose in the active layer. The Gafchromic EBT3 film has universal sensitivity in various energy ranges (X-ray and gamma) and good sensitivity in the area of average dose levels, where the film has almost a linear response [5]. The best response of the exposed film can be obtained by measuring the optical transmission coefficient at the red wavelength in the range of the polymer absorption peak, i.e., about $\lambda = 635$ nm [6]. While at other wavelengths, for example, $\lambda = 400$ nm, the film is almost insensitive to radiation, which allows, for example, using this wavelength to organize a reference measuring channel.

In order to study the possibility of using the Gafchromic EBT3 film as a sensing element in a compact dosimeter, the authors carried out model calculations [7] confirming the possibility of using this material for personal radiation monitoring.

**Operation principle of the device**

The distinctive features of the proposed personal portable dosimeter of the effective dose are:

- lack of a built-in power supply;
- use of a radio frequency communication channel for transmission of measured information;
- two modes of operation: passive – for accumulating data on the effective dose and active – for transmitting information to external systems for reading and accumulating information.

The main element of the proposed personal portable dosimeter of the effective dose is the detector (Fig. 1). It contains two photoconverters 3 and 9, covered by the lightproof shell 2 and located on the dielectric substrate 1. The photosensitive area of one of the photoconverters is covered with a film sensor 4 sensitive to the accumulated dose, and the other is covered with a compensator 8 with an optical transmission coefficient equal to the optical transmission coefficient of the film sensor 4 without irradiation, which receive optical radiation from the source 7 located on the substrate in the same plane between the photoconverters 3 and 9 and the optical flow divider 5 with the outer mirror coating 6.

To organize optical measurements, an optical signal source with a wide radiation pattern is required. LED emitting at a wavelength of $\lambda = 635$ nm is suitable for this purpose. The luminous flux of the LED shall be divided into two optical channels; one of them will contain the element sensitive to ionizing radiation, and the other will contain a compensator, showing the change in the optical properties of the sensor substrate material during the operation of the device. In addition, the presence of the second measuring channel is necessary for relative measurements of the optical transmission coefficient, performed on the first channel.

Each channel for converting optical signals into electrical signals uses the same type of photoconverters with corresponding spectral characteristics. After digitization, the received electrical signals are supplied to the microcontroller, where they are mathematically processed. Then the data is transmitted to the accounting system via the radio channel.

Ionizing radiation continuously interacts with the sensing element. Information about the dose is recorded in the form of an increase in sensing element optical absorption at a wavelength of 635 nm. Reading of this information is carried out optically at the time of interaction of the personal dosimeter with the information processing and storage system. The personal code

![Figure 1. Diagram of the detector: 1 – dielectric substrate; 2 – opaque cover; 3 – the first photoconverter; 4 – film sensor, sensitive to the accumulated dose; 5 – optical flow divider; 6 – mirror coating; 7 – source of optical radiation; 8 – compensator of the optical transmission coefficient; 9 – second photoconverter](image)
of the portable personal dosimeter is also transmitted at the time of the interaction. Further processing of information and its personal binding are carried out directly in the information system. The portable dosimeter does not contain a built-in power source, since the energy required for the device is transmitted via a radio channel at the time of interaction with the reader.

A schematic flow diagram of the personal portable dosimeter is shown in Fig. 2.

Electrical signals of photoconverters are fed to the analog-to-digital converter (ADC) and then to the microcontroller. The microcontroller performs processing of the incoming signals and prepares them for transmission to the information system through the transmitting module and the device antenna. The entire electronic part of the portable dosimeter starts and performs its functions within the time required for interaction with the external reading system, since the power is supplied in a non-contact way.

The physical model of the accumulated dose conversion into the electrical signal is as follows.

LEDs are characterized by Lambert’s distribution of radiation [8]. The beam emerging from the chip at an angle \( \vartheta \) with the normal to the semiconductor-air interface is refracted at an angle \( \jmath \) also with respect to the normal.

The luminous flux from such LED can be roughly estimated as follows:

\[
\Phi_0 = \frac{P_{\text{source}}r_0^2}{4\pi r^2 n_s^2} \cos \vartheta ,
\]

where \( P_{\text{source}} \) is the radiation power emitted from the semiconductor, \( W \); \( n_s \) is the air refraction index; \( r \) is the distance to the measurement point, \( \mu m \); \( n_s \) is the semiconductor refraction index.

The luminous fluxes are the same \( F_{01} = F_{02} = F_0 \) for the two optical channels implemented in the dosimeter.

When the luminous flux with the intensity of \( F_0 \) passes through a layer of a substance (solution), its intensity decreases to \( F \) as a result of absorption in the layer, reflection, and scattering.

The relationship between the intensities of the luminous fluxes \( F_0 \) and \( F \) is determined by the Beer-Lambert-Bouguer law:

\[
\Phi = \Phi_0 e^{-al},
\]

where \( a \) is the absorption coefficient, \( \mu m^{-1} \); \( l \) is the thickness of the absorbing layer, \( \mu m \).

**Experimental studies**

To find out whether the film is suitable for use as a sensing element in a small-sized dosimeter device, experiments aimed at determining the transmission coefficient of the EBT3 film after exposure to x-ray radiation were carried out.

![Figure 2. Block-chart of the personal portable dosimeter](image-url)
The EBT3 film samples (25×12 mm in size) were irradiated in the X-ray range using the Xstrahl 150 therapeutic system. System specifications:

- anode voltage range – 10–150 kV;
- X-ray tube current – up to 30 mA;
- maximum generator power – 3 kW;
- thickness of the half-attenuation layer: minimum – 0.2 mm Al and maximum – 1.0 mm Cu (equivalent to 13 mm Al);
- focal spot size – 7.5 mm;
- anode material – tungsten.

The device is completed with a set of applicators with a diameter of 1.5 to 15.0 cm.

The samples were irradiated at the following parameters:

- voltage – 140 kV;
- current – 12 mA;
- X-ray filter – copper;
- anode material – tungsten.

In the course of the experiment, the researchers sequentially irradiated the sets of film samples (10 series, eight samples in each series), while the value of the delivered dose was adjusted by increasing the exposure time.

As a result, it was determined that the samples under study begin to noticeably change their transparency at doses of about 5 mGy.

The transmission spectra of the samples before and after irradiation were measured using the SF102 spectrophotometer.

The dependence of the optical transmission coefficient $T$ of the EBT3 film on the accumulated dose for two wavelengths is shown in Fig. 3.

Curve 1 can be approximated by the following equation

$$T = 10^{-5} D^2 - 0.0242 D + 22.536,$$

where $D$ is the absorbed dose, mGy.

In this case, the dependence of the luminous flux transmitted through the first channel on the accumulated dose can be determined by the formula

$$\Phi_1 = \frac{\Phi_0 T}{100}. \quad (3)$$

As shown in Fig. 3 (curve 2), $\Phi_2$ does not depend on the accumulated dose at 400 nm. This can be used for calibration, for example, in the single-channel implementation of the sensing element.

Photoconverters (phototransistors) based on silicon are used as sensors for measuring optical density. During the passage of the luminous flux received from the light-emitting diode through two optical channels, one of which contains a radiation-sensing element, a significant decrease in the luminous flux of this channel occurs. The electrical signals received on identical photodetectors in different channels are also different. In this case, the difference between the signals of photodetectors carries information about the change in the absorbed dose.

**Description of the experimental sample of the effective dose dosimeter**

Based on the flow diagram (see Fig. 2), an experimental sample of the small-sized effective dose dosimeter with data transfer using RFID technology was developed.

A schematic diagram of the device is shown in Fig. 4. The device consists of the following main components:

- U1 – control microcontroller STM8L051F3P6;
- U2 – EEPROM with a capacity of 512 bytes M24LR04E with dual interface (wireless RFID 13.56 MHz ISO15693 ISO18000–3 mode 1 and I2C bus) and with the ability to power external devices from the RFID reader field energy;
- U3 – four-channel 16-bit analog-to-digital converter ADS1115 with I2C interface;
- U4 – LP2985IM5–2.5 low noise voltage regulator with shutdown;
- U5, U6 – phototransistors PT15–21C/TR8 (included in the sensor);
- LED1 QTLP650C–R (included in the sensor);
- stripline antenna for M24LR04E (dimensions 4.5 x 6.5 cm, six turns).

The developed device is capable of performing the following procedure. After contact with the RFID reader field and in the case of sufficient field intensity, the voltage appears at the output $E_0$ of the M24LR04E chip, after which the buffer capacitor $C_3$ starts charging.
When the voltage is above 1.8 V, the STM8L051F3P6 microcontroller starts operating which cyclically (every 50 ms) measures the supply voltage with its own analog-digital converter, waiting for the buffer capacitor to be charged. When the supply voltage is 3.1 V, the microcontroller turns on LP2985IM5–2.5, which supplies a stabilized voltage of 2.5 V to the U5-U6 PT15–21C/TR8 photodetectors and the LED1 QTLP650C-R of the sensor.

After that, the microcontroller starts reading the values from the dividers midpoints of the sensor phototransistors and control of the current flowing through the sensor LED, using the ADS1115 analog-to-digital converter. The inputs AIN0 and AIN1 are used for reading the values from the dividers midpoints, and the inputs AIN2 and AIN3 in the differential mode are used for reading the values from the control of the current flowing through the LED.

After completing the procedure of reading values from the sensor, the microcontroller calculates the difference in the illumination of the test phototransistor and phototransistor covered by the film sensor and records the result to EEPROM M24LR04E.

If all the measurement and recording procedures are successfully completed, the microcontroller lights the LED2 LED to visually monitor the end of the measurement procedure. Data recording is performed cyclically. EEPROM stores 16 recent measurements. They can be read using a standard RFID reader.

In order to eliminate the effect of the thermal drift of electronic components, tests were carried out in a thermostatic container at 25 °C. The thermistor TH1 was introduced into the circuit for the subsequent calibration of the device at various ambient temperatures.

The external view of the device is shown in Fig. 5.

Experimental studies, in which interchangeable irradiated EBT3 films were used as sensors, were conducted to confirm the performance of the device. The values of the voltage on phototransistors and their difference as a percentage of the test channel voltage were measured using the dosimeter depending on the radiation dose of the film (Fig. 6).
Fig. 6 shows that the sensitivity of the developed dosimeter is expected to be 0.034%/mGy. The lower dose limit of sensitivity for this device is 1 mGy.

The error of dose measuring by this method does not exceed 0.25 mGy.

Conclusion

A personal portable dosimeter of an effective X-ray dose has been developed. The sensing element of the dosimeter is the EBT3 X-ray-sensitive film, which continuously changes its transparency under the action of ionizing radiation (passive mode). The dosimeter includes a microcontroller device estimating changes in the accumulated dose by determining the degree of transparency of the sensing element. The specific feature of the device is the lack of a built-in power source. The dosimeter is supplied with a radio frequency data transmission system. The active operating mode of the dosimeter is implemented solely at the moments of data reading by external RF devices.

The main technical results of the development are the reduction of the weight and dimensions parameters of the small-sized portable personal dosimeter of the effective dose, increase in the measurement speed and interpretation of the measurement results, as well as an increase in the functionality. The expected sensitivity of the developed dosimeter is 0.034%/mGy. The lower dose limit of sensitivity for this device is 1 mGy. Thus, the lifetime of the personal device for measuring the effective dose of ionizing radiation due to the absence of its own power source is limited only by the maximum dose of radiation that can be registered and by the ability of the photoreceiver to record the optical flow passing through the film sensor, which darkens as a result of the received dose exposure.

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