UDK 62-783.1

D.O. Chalyy, *Candidate of Science (Engineering)*
(Lviv State University of Life Safety, Lviv, Ukraine)

THERMAL FIRE ALERTER ON FIBER-BASED OPTICAL TEMPERATURE SENSOR FOR OPERATION UNDER IONISING IRRADIATION

Building working model of radiation-resistant fiber-based optical temperature sensor and investigating of its measuring and other functional characteristics are performed in this paper. A signal response model was developed for the fiber optical temperature transducer based on chalcogenide glass of the $Ge_{0.18}As_{0.18}Se_{0.64}$ composition. Advantages of proposed sensor used in thermal fire alerter are analyzed including combined ones as well as possible ways of its modification.

Key words: fire alerter, fiber-based optical sensor, ionizing radiation, chalcogenide glass.

Д.О. Чалий

ВОЛОКОННО-ОПТИЧНИЙ СЕНСОР ТЕМПЕРАТУРИ ТЕПЛОВОГО ПОЖЕЖНОГО СПОВІЩУВАЧА ДЛЯ РОБОТИ В УМОВАХ ІОНІЗУЮЧОГО ОПРОМІНЕННЯ

Побудовано робочу модель радіаційно стійкого волоконно-оптичного сенсора температури та досліджено його вимірювальні та інші функціональні характеристики. Було промодельовано сигнал відгуку такого волоконно-оптичного сенсора температури на основі халькогенідного скла хімічного складу $Ge_{0.18}As_{0.18}Se_{0.64}$. Проаналізовано переваги використання запропонованого сенсора у пожежних сповіщувачах (в тому числі комбінованих) та можливі шляхи їх модифікації.

Ключові слова: пожежний сповіщувач, волоконно-оптичний сенсор, іонізуюче випромінювання, халькогенідне скло.

Д.А. Чалый

ВОЛОКОННО-ОПТИЧЕСКИЙ СЕНСОР ТЕМПЕРАТУРЫ ТЕПЛОВОГО ПОЖАРНОГО ИЗВЕЩАТЕЛЯ ДЛЯ РАБОТЫ В УСЛОВИЯХ ИОНИЗИРУЮЩЕГО ОБЛУЧЕНИЯ

Построена рабочая модель радиационно стойкого волоконно-оптического сенсора температуры и исследовано его измерительные и другие функциональные характеристики. Было промоделировано сигнал отклика такого волоконно-оптического сенсора температуры на основе халькогенидного стекла химического состава $Ge_{0.18}As_{0.18}Se_{0.64}$. Проанализировано преимущества использования предложенного сенсора в пожарных извещателях (в том числе комбинированных) и возможные пути их модификации.

Ключевые слова: пожарный извещатель, волоконно-оптический сенсор, ионизирующее излучение, халькогенидное стекло.

Introduction

Today fire statistics shows that the number of fires continually increases [1,2], being accompanied by the simultaneous increase in the number of victims, size of caused material losses and environmental damage. Analysis of the practice of large fires fighting shows that most often fires fighting actions were applied at the too late stage when the fire goes to the most intense stage of destruction of buildings. Despite of the large variety of fire alert system, the problem of early detection of fire signs and timely initiation of fires fighting process remains unresolved, partially through imperfections of existing instruments for detection of fire signs. Even more acute problem of such equipment obeying for objects with increased levels of ionizing radiation. It is obviously that negative affects of the fire at such objects as nuclear power plants (NPPs) can have global catastrophic character for all humanity; sad example of what is known occasions at the Chornobyl and Fukushima NPPs [3]. This problem for Ukrainian NPPs became more exacerbated owing to equipment for their fire alarm systems (FAS) was designed several decades ago [4-5] and now it is morally and physically antiquated. Moreover, replacement of such equipment in areas with increased level of radiation is a complex technical challenge. It should be noted here that considering of fire safety as an integral part of NPP safety, the IAEA recommends [6] to apply the principle of physical diversity and redundancy (duplication) in the control of the state of dangerous objects. Above mentioned testifies for necessity to revise approaches for the early detection of fire signs at the objects and areas with radiation level exceeding the normal conditions. Analysis of specialized tools for control of radiation-hazard objects [7] reveals that, on the one hand, (1) using of fiber-based optical sensors (FBOSs) of physical parameters of the object state is the dominant trend and, on the other hand, (2) existing temperature FBOSs [8-9] does not have sufficient radiation hardness to ensure the reliability of their functioning for a long time.

That is why a series of previous works of author [10-13] was devoted to investigation of chalcogenide glasses (ChGs) of $Ge_xAs_xSe_{1-2x}$ system ($0.05 \leq x \leq 0.30$) as promising temperature-sensitive and radiation-resistant media for the development of temperature FBOSs for operation under ionizing irradiation. Particularly, ChGs with $x = 0.18$ ($Ge_{0.18}As_{0.18}Se_{0.64}$) and close chemical composition were shown to be the best materials for application as active media for temperature sensors owing to their temporal stability of properties, thermal sensitivity up to 200 °C and radiation resistance up to 1 MGy absorbed dose [12-13].

In this paper, it was built the working model of such temperature FBOS, investigated its measuring and other functional characteristics, evaluated prospects for using in thermal and combined fire alerter for NPPs and other objects with increased levels of ionizing radiation.

Model of the temperature-induced changes in optical properties of the sensing element based on $Ge_{0.18}As_{0.18}Se_{0.64}$ ChG

Temperature-induced long-wave shift of the fundamental optical absorption edge (FOAE) [13] is a physical basis for operation of temperature FBOS [11]. It is know also that FOAE of the most ChGs is described by the phenomenological model of modified Urbach rule for glassy semiconductors [14], so for using of such a description is necessary to establish the model parameters from the experiment. With this aim, optical transmission spectra of $Ge_{0.18}As_{0.18}Se_{0.64}$ ChG were measured *in situ* using a spectrophotometer AvaSpec-2048 (*Avantes, Netherlands*) and specially designed temperature chamber at temperatures ranging from ambient to 200 °C. Presented at the Fig. 1 experimental data (recalculated in the form of optical absorption coefficient) in semi-logarithmic scale confirm that in the investigated temperature range the FOAE of $Ge_{0.18}As_{0.18}Se_{0.64}$ ChG shifts in parallel testifying for the modified Urbach rule with a temperature-independent slope of the absorption edge spectral dependences [14]:

$$\alpha(E,T) = \alpha_g \exp\left(\frac{E}{E_0} + \frac{T}{T_0}\right), \tag{1}$$

where α_g is a constant, T_0 is a characteristic temperature (determined from the experiment and having no clear physical sense), and $1 / E_0$ is a temperature-independent logarithmic slope of the spectral dependence. Approximation of the experimental data in Fig. 1 allowed to parameterize the empirical expression of the optical absorption coefficient α of sensing material on the energy of probing light E and temperature T in the form:

$$\alpha(E,T) = 3{,}86 \cdot 10^{-17} \exp\left(\frac{E}{0{,}0518} + \frac{T}{48{,}31}\right), \tag{2}$$

where the dimension of α is [cm^{-1}], energy E – [eV], and absolute temperature T – [K]. Equation (2) allows to model temperature behavior of the optical absorption of ChG, being the basis for modeling of signal characteristics of ChG-based FBOS.

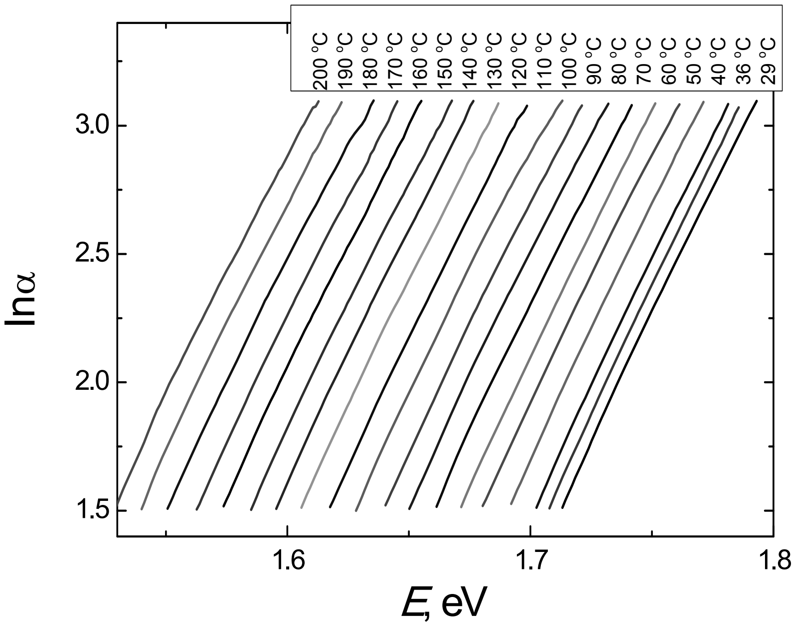

Fig. 1. *Dependences of logarithmic optical absorption coefficient on the probing light energy in the FOAE region of* $Ge_{0.18}As_{0.18}Se_{0.64}$ *ChG for different temperatures.*

Modeling of transforming characteristics of ChG-based temperature FBOS

The working scheme of the temperature FBOS of the probing type and design of the primary converter are shown in Fig. 2. Light from source 1 goes through the optical fiber to the optical splitter 2, and then to the primary converter 3, constructed from sensing element in the form of ChG plate 4, situated at the end face of the optical fiber, and a mirror 5 on the outer side of end face. Then light reflects from the mirror 5 and passes again through the sensing element, and finally going back by the fiber to splitter 3 reaches the photodiode detector 6. As the light source in our analysis, we considered commercially available LEDs with known characteristics and relative low cost, in particular LEDs with optical fiber output produced by Mightex Systems (USA) [15], which offers quite a wide range of monochrome LEDs with roughly comparable emission half-width in 0.06-0.1 eV (35-55 nm) and different position of maximum emission from ultraviolet to infrared range of the optical spectrum. Spectral emission intensity distribution was described by the Lorentz function with parameters, which are determined from the approximation of the LED emission characteristic $I_{LED}(E)$. As the photodetector, we considered produced by Thorlabs (USA) the silicon photodiode FDS1010-CAL with a calibrated conversion characteristic, since it is typical for conventional silicon photodetectors and quantitative data for calibration of its spectral dependence of current response is available at the web-site of Thorlabs [16]. Quartz fiber is considered as a fully transparent within interesting for analysis wavelength range. Losses on the distribution of the optical signal, reflection at the borders and in the optical splitters were not considered in according to the assumption that they have no essential spectral features in the analyzed wavelength range, and do not affect on the relative change in the intensity of the measured signal caused by temperature changes of FOAE of sensing element.

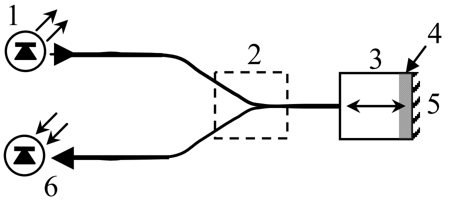

Fig. 2. *Optical scheme of the temperature FBOS of the probing type: 1 – light source (LED); 2 – optical splitter; 3 – primary converter; 4 – ChG-based sensing element with a mirror 5; 6 – photodiode.*

Intensity of the light with some photon energy E, which passes through the temperature-sensitive sensor element, is expressed by Bouguer-Lambert law. Thereby, intensity of the light with photon energy E, which passes through the whole optical scheme and is recorded by photodetector, can be expressed as follow:

$$I(E,T) = I_{LED}(E) \cdot \exp\left(-\alpha(E,T) \cdot 2d\right) \cdot I_{PD}(E), \tag{3}$$

where $\alpha(E,T)$ – dependence of absorption coefficient of temperature-sensitive ChG on the photon energy and temperature, given by equation (1) with the experimentally-obtained model parameters; d – thickness of the plate of ChG-based sensing element; factor 2 reflects that twice passing of the light through the sensing element doubling the optical path in it; $I_{LED}(E)$ – dependence of the emission intensity on the photon energy in according to Lorentz function; $I_{PD}(E)$ – spectral dependence of the photodetector current response.

The level of the measured signal from the photodiode, i.e. sensor output signal, as a function of temperature (which is the input parameter of sensory transformation) is light-sum throughout the actual spectral region and can be shown as:

$$I(T) = \int I_{LED}(E) \cdot \exp\left(-\alpha(E,T) \cdot 2d\right) \cdot I_{PD}(E)dE. \tag{4}$$

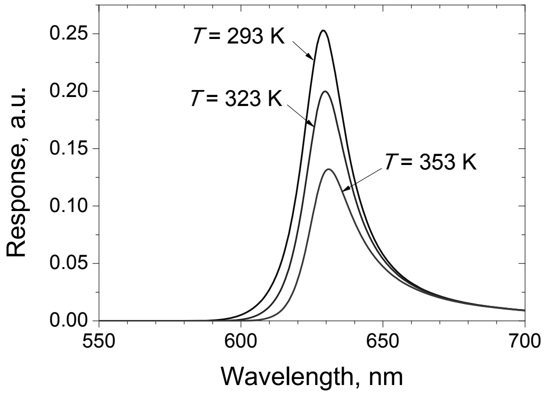

Fig. 3. *Spectral dependences of signal response at different temperatures for temperature FBOS with double thickness of sensing element in 1 mm and red LED with maximum emission at 628 nm.*

Equation (3) allows to analyze the spectral features of the measured signal, as well as the equation (4) – the output signal of the primary temperature transducer. Fig. 3 shows the typical spectra of current response of the sensor (at the example of using of LED with a wavelength of 628 nm radiation maximum as a source). Temperature increase leads to the long-wave shift of the FOAE position of the sensing element and can extinguish the optical system transmission in some temperature range.

Level of the sensor output signal (defined by the equation (4)) as a function of temperature is shown in Fig. 4a for LEDs with different positions of the maximum emission in yellow-red spectrum region. As it seen, the temperature dependence is characterized by the quasi-linear part with the highest sensitivity in a certain temperature range. Therefore, for the same sensing element we can choose special light source to adjust the temperature range of highest sensitivity. On the other hand, the position of FOAE of the sensing element and the position of the temperature-related linear range of the highest sensitivity depends on the optical beam path in an environment that is on the thickness of the sensing element in the light direction. Calculated transformation characteristics of the ChG-based temperature FBOS are shown in the Fig. 4b for different values of double thickness of sensing element and the same red LED as the light source. It is seen that double thickness of sensing element varying from 0.5 to 1 mm (that is in the technologically-accessible range) leads to the linear part of the sensor highest sensitivity in the vicinity of temperature range from 0 to 100 °C.

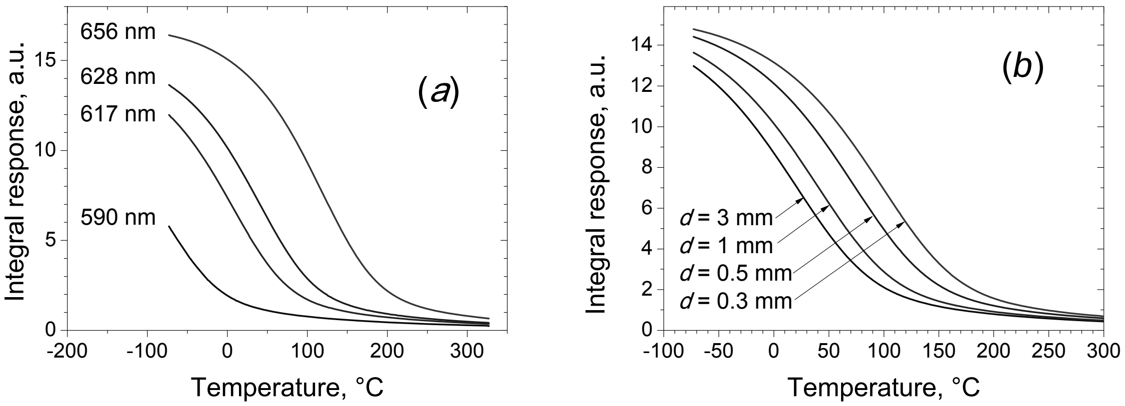

Fig. 4. *Temperature dependences of the integral signal response of the temperature FBOS: for 1 mm double thickness of sensing element and different LED of yellow-red spectrum region (a) and for different double thickness of sensing element and red LED with maximum emission at 628 nm [16] (b).*

Optimization of the characteristics of thermal fire alerter and analysis of its advantages

Further analysis is reasonable to be performed for the exploitation-required sensor characteristics. The operation threshold of the maximum-type thermal fire alerter is often configured near the 60 °C [17-19]. Therefore, for LED with maximum emission on 628 nm we choose such sensing element thickness which provide the operation threshold near the middle of linear conversion characteristic. Fig. 5 shows calculated conversion characteristic of the sensor with a thickness of 0.35 mm (double thickness of 0.7 mm), where the response intensity is normalized to the response value for 20 ºC temperature. It is seen that optimal sensor characteristics correspond to the linear region of the highest sensitivity in the temperature range from 25 to 90 °C, while sensor sensitivity equals to 0.8% of registered light intensity change per 1 °C in respect to the intensity value at the 20 °C temperature. It means that measured flow intensity will decrease by more than 30% or about the level of 3 dB at 60 °C temperature. Such intensity changes can be relatively easy and with sufficient accuracy registered by conventional photometers, since typical sensitivity threshold of the optoelectronic sensors of fire alerters is significantly better than 0.1 dB [17]. The absolute error of temperature measurements by such sensor does not exceed ± 1.5 °C in a linear range of measuring characteristics if photometric accuracy is about 1 %. This accuracy is higher than its of typical thermal fire alerters.

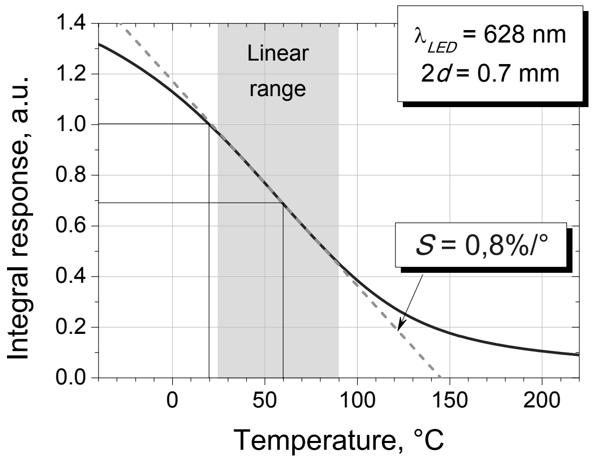

Fig. 5. *Calculated conversion characteristic of the probe-type temperature FBOS with a* $Ge_{0.18}As_{0.18}Se_{0.64}$ *ChG as a sensing element. There are used sensing element with 0.7 mm double thickness, LED with maximum emission at 628 nm and silicon photodetector. Characteristics is normalized in respect to the intensity value at the 20 ℃.*

The linear part of the measuring characteristic of temperature FBOS, that is range of stable sensitivity, allows to put and solve the problem of temperature measurement with smart functions of processing of the obtained data, namely the rapid prediction of the next values. Such measurements are based on an analysis of the rate of measured values change and allows to estimate with some accuracy the future temperature values. To implement such a measuring, electronic scheme (that provides signal conversion from primary converter) should determine not only the temperature, but the current value of the rate of temperature changes too. The temperature growing rate at the stable sensitivity of the primary convertor corresponds to the rate of change of the measured signal. Therefore, estimation of the speed of temperature changing rate is easy to provide using known circuit approaches. Obviously, under the growing of temperature changing rates in the case of fire, there is not necessary to wait for the sensor reacting on the critical temperature (typically 60 °C), the achievement of which should initiate fire-extinguishing means. It can be predicted earlier by the current temperature value that is below the critical and the value of temperature growing rate. Based on the fact that the thermal maximum-differential-type alerters triggering not only by exceeding the threshold temperature, but also by exceeding the temperature growing rate of 3-7 ºC/min. [20], so we can activate the alarm "fire" in 4-7 minutes earlier by determining the critical temperature growing rate. The specific values of critical rate and forecasting time should be considered on the basis of the real development of fire alerters and their experimental tests, including the models of fire progress and known approaches to the estimation of predicted values of the measured signal.

One of the most important characteristics of the fire alerter is forecasting time that characterizes the sensor inertia and therefore the speed of its response to the changes in environmental temperature. Typical values of forecasting time of the thermal alerters vary from a few to hundred of seconds [18-19]. The response time on the temperature changes for FBOS is limited only by the rate of heat transfer process from the controlled object to the sensitive element, which in turn limited by the finite heat conductivity and heat capacity of the sensor material and optical fiber. It means that a thin plate of the sensing element (with a thickness less than 1 mm) should provide minimum inertia of the sensor.

It should be noted that the analysis of signal sensitivity of the proposed temperature FBOS based on radiation-resistant ChG in its simplest implementation does not exclude the application of known solutions used in fire alerter systems, including the combined two-functional detector of temperature and smoke or three-functional detector of temperature, smoke and flame simultaneously. For optoelectronic sensors it is relatively easy to implement, because measuring of the optical signal changes is the physical basis of signal registration in all cases. Furthermore, an additional advantage of such systems is the ability to use common signal transfer channels that simplifies technical implementation, increases reliability and noise immunity, reduces costs, simplifies installation and improves maintainability. So, using of considered optoelectronic thermal alerter allows to develop a combined alerters with a fully optical signal recording, while the existing types of combined alerters join optical and thermoresistive sensors in one system [17].

Additionally, it should be mention that one of the main applications ChG are optical fibers. A huge variety of ChG compositions and the corresponding optical properties gives possibility to use them in temperature FBOS for operation under ionizing radiation not only as a sensitive elements, but as a passive waveguide too. Obviously, in this case the FOAE of ChG for waveguide at room temperature should be shifted to the short-wave region in respect to FOAE of thermal-sensitive ChG (for excluding of prevention of the sensing element operation). On the other hand, the using of thermal-sensitive ChG as a fiber allows to develop temperature FBOS of distributed type, which can react on the temperature increase of fiber with high sensitivity.

Conclusions

It was developed in this work the principles for practical development of radiation-resistant temperature FBOS for thermal fire alerters based on ChG of $Ge_{0.18}As_{0.18}Se_{0.64}$ composition, which exhibits a wide range of operating temperatures, high time stability and radiation resistance. It was established that the temperature behavior of the FOAE of this glass corresponds to the modified

Urbach rule and the parameters of the respective model were determined. The model of signal response of the temperature FBOS of the probing type was built and the analysis of its sensitivity characteristics and linearity range was performed. It was shown selection of wavelength of monochrome LED emission and thickness of sensitive element allows to control the position of the linear region of the highest measuring sensitivity and to achieve sensitivity of the temperature measuring near 0.8 %/°C. that allows with sufficient accuracy to measure the temperature by conventional photometric means. It was noted that dynamic characteristics of considered temperature FBOS are limited only by the inertia of the heat exchange with sensing element of optimized extremely small mass. It was analyzed the possible ways of modifying the proposed temperature FBOS to provide the smart functions of processing of the obtained data, namely the rapid prediction of the next temperature values. Particularly, it was shown that due to sufficient linear region of the highest measuring sensitivity of temperature FBOS, it is technically easy to implement the estimation of the temperature in the nearest time through the temperature growing rate, which potentially reduces the time of the fire detection for 4-7 minutes.

References

1. Стан із пожежами та наслідками від них в Україні у першому півріччі 2012 року [Електронний ресурс]: за даними УкрНДІЦЗ МНС України / УкрНДІЦЗ МНС України; ред. Р. Климась, Д. Матвійчук. – 2012. – С. 4. Режим доступу: http://undicz.mns.gov.ua/files/2012/7/23/AD_06_12.pdf.

2. Стан із пожежами та їх наслідками в Україні за 2011 рік [Електронний ресурс]: за даними УкрНДІЦЗ МНС України / УкрНДІЦЗ МНС України; ред. Р. Климась, Д. Матвійчук. – 2012. – С. 19. Режим доступу: http://undicz.mns.gov.ua/files/2011/12/31/stat_fire_12_2011.zip.

3. Поярков В. Основные знания о ядерной опасности: уроки Чернобыля и Фукусимы. EUR-OPA 2011. 20 с.

4. Аналітичний звіт про стан пожежної безпеки в ДП НАЕК «Енергоатом» за 2010 рік. 54 с.

5. Пожежна небезпека українських АЕС [Електронний ресурс]: http://security-ua.com/index.php?option=com_k2&view=item&id=1868:pozhezhna-nebezpeka-ukrayinskih-aes&Itemid=574&lang=ru.

6. Серия норм МАГАТЭ по безопасности. Руководство № NS-G-1.3: Системы контрольно-измерительных приборов и управления, важные для безопасности атомных электростанций. – Вена, 2008. – 127 с.

7. Ferdinand P. Optical fiber sensors for the nuclear environment / P. Ferdinand, S. Magne, O. Roy, V. Dewynter Marty, S. Rougeault, M. Bugaud // Optical Sensors and Microsystems / Ed. Martellucci S., Chester A.N. and Mignani A.G. – New York: Kluwer Academic Publishers, 2002. – P. 205-226.

8. Berghmans F. Optical fiber semiconductor absorption temperature sensors for temperature monitoring in a gas-cooled nuclear reactor / F. Berghmans, F. Vos, M. Decteron, L. Van Den Durpel, D. Marloye, I. Verwimp // Proc. of SPIE. – 1996. – Vol. 2839. – P. 182-189.

9. Berghmans F. Evaluation of three different optical fibre temperature sensors types for application in gamma radiation environment / F. Berghmans, F. Vos, M. Decteron // Proc. of IEEE. – 1998. – Vol. 4071. – P. 424-429.

10. Чалий Д.О., Шпотюк М.В., Убізський С.Б., Шпотюк О.Й. Халькогенідне скло системи $Ge_xAs_xSe_{1-2x}$ як активне середовище для радіаційно-стійких пожежних сповіщувачів // Науковий вісник УкрНДІПБ. – 2012. – № 2 (26). – С. 144-149.

11. Чалий Д.О. Сенсори температури на основі халькогенідних стекол для детектування осередків загорання на ранніх стадіях / Д.О. Чалий // Збірник наукових праць «Пожежна безпека» . – № 21, 2012.– С. 171-176.

12. Чалий Д. Халькогенідні скла для високонадійних сенсорів температури / Д. Чалий, М. Шпотюк // Вісник Національного університету „Львівська політехніка”, Серія Електроніка, т. 734, 2012, с. 17-20.

13. Shpotyuk M., Chalyy D., Shpotyuk O., Iovu M., Kozdras A., Ubizskii S. Are the temperature sensors based on chalcogenide glass possible? // Solid State Phenomena, v. 200, 2013, p. 316-320.

14. Вайнштейн И.А., Зацепин А.Ф., Кортов В.С. Особенности проявления правила Урбаха в стеклообразных материалах // Физика и химия стекла. – 1999. – Т. 25, № 1.– С. 70 – 80.

15. Filtered Fiber-Coupled LED Light Sources. Каталог продуктів фірми Mightex Systems. [Електронний ресурс]; режим доступу: http://www.mightexsystems.com.

16. Si Photodiodes with NIST Traceable Calibration, Thorlabs. [Електронний ресурс]; режим доступу: http://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2822.

17. Сайт фірми «Систем Сенсор Фаир Детекторс» [Електронний ресурс]; режим доступу: http://www.systemsensor.ru.

18. Абрамов Ю.А. Точечные тепловые пожарные извещатели максимального типа / Ю.А. Абрамов, Е.В. Куренной. – Х.: АГЗУ, 2005. – 129 с.

19. Семкив О.М. Анализ характеристик и параметров тепловых пожарных извещателей // Проблемы пожарной безопасности. Сб. научн. тр. – Харьков: УГЗУ. – 2011.– Вып. 29.– С. 156-160.

20. Шаровар Ф.И. Сравнительная оценка эффективности применения тепловых максимальных, дифференциальных и дымовых пожарных извещателей // Системы безопасности S&S.– М.: Grotesk, 2003.– № 1 (49).

References

1. Klymas, R. and Matviychuk, D. (2012). *State of fires and their consequences in Ukraine in the first half of 2012*. Kyiv: Ukrainian Research Institute of Civil Protection. Retrieved from http://undicz.mns.gov.ua/files/2012/7/23/AD_06_12.pdf (in Ukr.)

2. Klymas, R. and Matviychuk, D. (2012). *State of fires and their consequences in Ukraine in the 2011*. Kyiv: Ukrainian Research Institute of Civil Protection. Retrieved from http://undicz.mns.gov.ua/files/2011/12/31/stat_fire_12_2011.zip (in Ukr.)

3. Poyarkov, V. (2011). *Basic knowledge about the nuclear threat: the lessons of Chornobyl and Fukushima*. EUR-OPA (in Russ.)

4. *Analytical report on fire safety in SE NNEGC “Energoatom” in 2010* (2011) (in Ukr.)

5. *Fire danger of Ukrainian NPP*. Retrieved from http://security-ua.com/index.php?option=com_k2&view=item&id=1868:pozhezhna-nebezpeka-ukrayinskih-aes&Itemid=574&lang=ru (in Ukr.)

6. International Atomic Energy Agency (2008). *IAEA Safety Standards Series. Safety Guide No. NS-G-1.3: Instrumentation and Control Systems Important to Safety in Nuclear Power Plants*. – Vein: IAEA.

7. Ferdinand, P., Magne, S., Roy, O. et al. (2002). *Optical fiber sensors for the nuclear environment*. In S. Martellucci, A.N. Chester and A.G. Mignani (Ed.). *Optical Sensors and Microsystems*. New York: Kluwer Academic Publishers.

8. Berghmans, F., Vos, F., Decteron, M. et al. (1996). Optical fiber semiconductor absorption temperature sensors for temperature monitoring in a gas-cooled nuclear reactor. *Proc. of SPIE, 2839, 182-189*.

9. Berghmans, F., Vos, F., Decteron, M. (1998). Evaluation of three different optical fibre temperature sensors types for application in gamma radiation environment. *Proc. of IEEE, 4071, 424-429*.

10. Chalyy, D.O., Shpotyuk, M.V., Ubizskii, S.B. and Shpotyuk, O.I. (2012). Chalcogenide glass of Ge$_x$As$_x$Se$_{1-2x}$ system as active media for radiation-resistant fire-alarm boxes. *Naukovyy visnyk UkrNDIPB (Scientific Bulletin of UkrRIPC), 2 (26), 144-149* (in Ukr.)

11. Chalyy, D.O. (2012). Temperature sensors based on chalcogenide glasses for early-stage detecting of fire hotbeds. *Zbirnyk naukovykh prac «Pozhezhna bezpeka» (Proceedings "Fire Safety"), 21, 171-176* (in Ukr.)

12. Chalyy, D. and Shpotyuk, M. (2012). Chalcogenide glasses for high-reliable temperature sensors. *Visnyk Natsionalnoho universytetu "Lvivska politekhnika", Seriya Elektronika (Bulletin of Lviv Polytechnic National University, Electronics), 734, 17-20* (in Ukr.)

13. Shpotyuk, M., Chalyy, D., Shpotyuk, O. et al. (2013). Are the temperature sensors based on chalcogenide glass possible? *Solid State Phenomena, 200, 316-320*.

14. Vainshtein, I.A., Zatsepin, A.F. and Kortov, V.S. (1999). Peculiarities of Urbach rule in glassy materials. *Fizika i khimiya stekla (Physics and chemistry of glass), 25 (1), 70-80* (in Russ.)

15. Mightex Systems. *Filtered Fiber-Coupled LED Light Sources*. Retrieved from http://www.mightexsystems.com

16. Thorlabs. *Si Photodiodes with NIST Traceable Calibration*. Retrieved from http://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2822

17. System Sensor. Retrieved from http://www.systemsensor.ru (in Russ.)

18. Abramov, Yu.A. and Kurennoy, E.V. (2005). *The point thermal fire alerters of maximum type*. Kharkiv: AGZU (in Russ.)

19. Semkiv, O.M. (2011). Analysis of characteristics and parameters of thermal fire alerters. *Problemy pozharnoy bezopasnosti (Problems of fire safety), 29, 156-160* (in Russ.)

20. Sharovar, F.I. (2003). Comparative evaluation of the effectiveness of the thermal maximum, differential and smoke fire alerters. *Sistemy bezopasnosti S&S (Security Systems S&S), 1 (49)* (in Russ.)

❖ ❖ ❖