Fiber-optic sensor for remote monitoring the $\gamma$-radiation of various powers

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Abstract. The necessity of improving the metrological characteristics and functional capabilities of the fiber-optic sensor for measurements at the large distances (more than 10 km) is substantiated. The new method for constructing a communication line with the fiber-optic sensor for controlling exposure dose in a large range of its variation (several orders of magnitude) in a remote mode is proposed. The functional capabilities of the sensor are determined; its connection setup and measurement limits are developed. The experimental results are presented.

1. Introduction

The development of scientific and technical progress led to the appearance of large number of facilities, both scientific and industrial, which use radioactive materials [1-4]. Every year the number of these increases, because of which has increased the number of cases of radioactive materials leakage (getting them into water, soil, into the atmosphere etc.) [1, 3, 5-8]. Moreover, the number of radioactive releases (mainly $\gamma$-radiation) outside the protective zone (through the protective screens and ceilings) has increased. It has led to a deterioration of the ecological situation in several regions [9-14]. Therefore, great attention is paid to constant control the radiation situation, both in the atmosphere and on territory of various facilities [5, 7, 8, 14-19].

The main interest is the probability of remote control the radiation situation in automatic mode. Such monitoring is necessary for facilities, where the possibility of radioactive materials leakage is high: in various land-based and sea-based systems of nuclear power plants and on the territories of test sites [4, 6, 8, 19-21]. In some cases, remote control should be realized at the distance more than 10 km from the location of the monitoring center. Moreover, the exposure dose $D_R$ in control zone can change by several orders in a short period of time. After the exposure dose is terminated, device takes measurements in normal mode after a while. In such operation conditions, it is extremely difficult to use most of dosimetry devices, because they often go off and can accumulate the radiation on the instrument case and functional units, which prevents normal operation due to a great danger to humans.
One of the perspective directions for such measurements is the use of fiber-optic sensors [22-24]. Fiber-optic sensors developed nowadays, which operation principle is based on the measurements of changes in laser radiation polarization under the \(\gamma\)-radiation influence, allow to register small \(D_R\) changes, which cause a decrease in the laser radiation power by 0.05 dB. At a high \(D_R\) values laser radiation in them is completely damped and sensor stopped its work for a long time. The relaxation process without interventions can take \(10^6\) s and more [22-24], because for measurements are used small powers (no more than 5 mW). The use of more powerful radiation can damage photosensitive layer in photodetector module. Therefore, developing of new models of fiber-optic sensors is extremely actual.

2. Principle of operation a fiber-optic sensor for remote monitoring \(\gamma\)-radiation on based the governance to color centers relaxation rate

The color centers appear in an optical fiber after ending the \(\gamma\)-radiation influence [22-24]. The amount of these defects depends on two radiation effects: displacement and ionization. The displacement is due to the atoms shift from a stationary state to an unstable. Due to this shift in the crystal lattice the vacancies are formed, the inter-site introductions of additional atoms occur, etc. In some cases, these defects can be unstable (if the radiation level is low enough for an optical fiber can recover due to relaxation processes to primary state). In the case, when radiation influence was too long or radiation level was too high, the displacement effect leads to the appearance of more difficult defects with the union of various defects (for example, defects which are connected to the presence of alloying additives, etc). As the result the crystal lattice destroys, and an optical fiber does not recover to the primary state.

The ionization effect is based on the formation of electron-hole pairs. An electron with high energy knock oxygen out of OH compounds and takes its place in the crystal lattice. In a case of alloying fiber core by the germanium oxide GeO\(_2\), oxygen is knocked out of this chemical compound. The increase in the amount of ionization atoms changes the electrical properties of the optical medium, that can lead to the change of the refractive index \(n\). The effects caused by ionization disappear after ending the \(\gamma\)-radiation influence, because the free charge carriers have a high mobility. But in some cases, when exposure dose is high or long, the free charge carriers can miss in the deep energetic levels of the optical material and make stable connections. It also leads to the impossibility of return the optical fiber to the initial state.

Relaxation process begins right after the formation of electron-hole pairs, which take part in the formation of color centers. Relaxation velocity depends on the value of exposure doasses of irradiation and the duration of the \(\gamma\)-radiation influence. It is possible to determine the presence of \(\gamma\)-radiation in its placement zone (using the data of preliminary calibration), if measuring the decrease of laser radiation power at the output of an optical fiber. But this process has some difficulties. Previous researches [22-24] showed, that the relaxation time after ending the radiation influence can take \(10^6\) and more. In this case next powerful \(\gamma\)-radiation influence cannot be recorder, and it will be extremely difficult to estimate the value of exposure dose \(D_R\). As the result the possibility of remote control of radiation situation will be stop for a long period. So, maintain the operability of fiber optical sensors becomes possible only in the case of control the relaxation rate of radiation color centers.

3. Experimental setup and research results

It is necessary to provide additional research of \(\gamma\)-radiation influence on the optical fiber for develop a new design of the fiber-optic sensor for remote monitoring the radiation situation. We have assembled earlier an experimental setup for these purposes [23,24]. Its block diagram is presented at the figure 1.

In the experimental setup was used modified transmitting optical module DMPO131-23M (company Dilaz) with a wavelength \(\lambda=1550\) nm and variation of radiation power from 0.1 to 5.4 mW. It was used as a continuous source of laser radiation. To measure losses, the classical formula was used:
where $P_{in}$ – the power input in to the optical fiber, $P_{out}$ – the power output from the optical fiber, $L$ – the length of the optical fiber.

\[ \alpha_s = \frac{10}{L} \lg \left( \frac{P_{in}}{P_{out}} \right) \] (1)

Figure 1. The block diagram of the experimental setup: 1 - laser transmitting module; 2 - power driver; 3 - polarizer; 4 - optical divider; 5 - optical power meter; 6 - мультиплексор; 7 - pulsed semiconductor laser; 8 - pulse power driver; 9 - source of $\gamma$ - radiation; 10 - control unit of the source of $\gamma$ - radiation; 11 - optical fiber; 12 - closed volume of a polymeric material; 13 - a device for changing the temperature; 14 - a device for controlling the dose of radiation; 15 - receiving optical module; 16 – optical adapter.

For connecting source, receiver and isolator together with the optical fiber are applied the detachable connections, which have typical losses $\alpha_{pc} = 0.2$ dB. There are 11 such connections. The losses in the optical adder are 0.46 dB. There are 2 such adders. The losses on the optical polarizer are 0.32 dB. Total losses on the connections and adders are 3.44 dB. For registration of low power of the laser radiation at the high losses in the optical fiber was used the receiving optical module DFDMSh40-16M (company Dilaz), which has highly sensitive in the wavelength range of 980-1650 nm. It is better to use a set of two devices from one company, because it allows to obtain a higher signal-to-noise ratio at a low power of laser radiation.

This experimental setup allows to conduct measurements both at the moment of $\gamma$-radiation influence and immediately after its termination, in contrast to the works, which were previously conducted by other scientists. Also, there is no large time interval between the time of the $\gamma$-radiation influence and the beginning of measurements. It allows to establish a number of new features for optical fibers, which relate to the color centers relaxation.

At the figure 2 as an example are presented the dependences of the $\alpha_s$ losses in single-mode fibers with the change of exposure dose $D_\gamma$ for various alloying percentage of optical fiber.

Analysis of the results obtained at the figure 2 showed, that an increase in alloying percentage increases the sensitivity of this optical fiber to the exposure dose of $\gamma$-radiation. It allows to register the changes in small $D_\gamma$ values, which decrease of the laser radiation power at the output of FOCL by 0.2 dB, when exposed to an optical fiber.

At the figure 3 as an example are presented the research results of velocity of the optical properties recovery after $\gamma$-radiation influence with a dose of 100 G.
Figure 2. Dependence of the $\alpha_s$ changes at a wavelength $\lambda=1550$ nm with irradiation dose $D_R$ for a single-mode fiber with a $\text{SiO}_2 - \text{GeO}_2$ core at $T = 294.2$ K. Charts 1, 2, 3 and 4 correspond to different alloying in %: 1.5; 4.0; 10.0 and 20.0.

Figure 3. Dependence of the $\alpha_s$ changes at a wavelength $\lambda=1550$ nm with irradiation dose $D_R$ for a single-mode fiber with a $\text{SiO}_2 - \text{GeO}_2$ core at $T = 294.2$ K. Charts 1, 2, 3 and 4 correspond to different alloying in %: 1.5; 4.0; 10.0 and 20.0.

Obtained results show that relaxation velocity of color centers higher with an increase of the alloying percentage. As a new design of the fiber-optic sensor, FOCL with a pure quartz core is proposed to connect to an optical fiber 200 m long with a $\text{SiO}_2 - \text{GeO}_2$ core and various alloying percentage (the alloying degree can be changed depending on the solving tasks). To recover an optical fiber, was decided to use the method developed earlier by us [16, 18], which is based on using an additional laser radiation with a wavelength $\lambda=1310$ nm and a dose of 100 G for pulsed and
continuous laser radiation. For conducting this research was used pulsed laser radiation with a duration of 0.1 s with various powers during 10 s.

![Figure 4](image1.png)

**Figure 4.** Dependence of the change in losses $\alpha_s$ with time $t$ at a wavelength $\lambda=1550$ nm for a single-mode fiber with a SiO$_2$ – GeO$_2$ core (alloying 10.0 %) and polymer cladding at $T=294.3$ K. Charts 1, 2 and 3 are correspond to different laser radiation powers in mW: 0; 40; 80.

![Figure 5](image2.png)

**Figure 5.** Dependence of the change in losses $\alpha_s$ with time $t$ at a wavelength $\lambda=1550$ nm for a single-mode fiber with a SiO$_2$ – GeO$_2$ core (alloying 10.0 %) and polymer cladding at $T=294.3$ K. Charts 1, 2 and 3 are correspond to different laser radiation powers in mW: 0; 20; 40.

Analysis of the obtained results shows that the use of additional laser radiation in communication line allows to control the relaxation velocity of color centers (the increase of additional radiation power significantly increase the relaxation velocity). It allows to recover the optical properties of an optical fiber in less 10 s. Moreover, it was found in research, that the use of pulsed laser radiation is more effective than continuous.

4. Conclusion

Obtained experimental results showed a reliable work of the developed sensor for remote control an exposure dose from 0.1 to 1000 G with an opportunity of operation mode recovery with using an additional laser radiation with $\lambda=1310$ nm, as in trunk FOCLs developed earlier [21-24]. It is difficult to use the method developed by us in fiber-optic sensors with the measurements, based on the polarization, because there is high probability to failure the photodetectors with high sensitivity used in them.
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