RT&A, Special Issue No 5 (75)
Volume 18, November 2023

FIBER-OPTIC SENSOR FOR FUNCTIONAL SECURITY OF THE OBJECT PERIMETER PROTECTION SYSTEM

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Abstract

As a result of the analysis, it was concluded that the existing fiber-optic sensors are mainly used to detect the place of unauthorized access. For this purpose, a fiber-optic sensor has been developed using G 655 optical fiber with the highest susceptibility to macrobending, which makes it possible to determine not only the fact of unauthorized access, but also the parameters of the penetrating object, namely its mass, to increase the measurement range of the attenuation of the branched signal of optical radiation due to amplification of this signal and the measurement limit of the body weight of the object of unauthorized access due to the choice of the spring stiffness coefficient. Experimental studies have been carried out to determine the susceptibility of various types of optical fiber to macrobending, the dependence of the attenuation of the optical radiation signal on the macrobending radius, the length of the macrobending arc, and the mass of the unauthorized access object.

Keywords: optical fiber, sensor, guarded object, macrobend, deformation, mass

I. Introduction

In fiber-optic sensors, as a sensitive element for detecting changes in information parameters about the state of a particular protected object, an optical fiber with the highest susceptibility to macrobending is mainly used, which expands the scope of their application.

Currently, many fiber-optic sensors have been developed that allow recording deformation, vibration, tilt angle, acceleration, displacement, pressure, as well as detecting unauthorized access to the perimeters of a protected object [2-5]. To measure deformations, vibrations and other mechanical effects, as a fiber-optic sensor to ensure the functional security of the perimeter security system of an object, optical fibers are mainly used, through which useful information is simultaneously transmitted [6]. The applicability of fiber optic technologies is determined mainly by immunity to electromagnetic fields and electrical safety. In case of unauthorized access to the perimeters of the protected object, external influences are created in the form of mechanical pressures, deformations and / or vibrations, which in turn leads to a change in the parameters of the transmission medium and, as a result, the parameters of the optical radiation signal transmitted through the optical fiber.

II. Formulation of the problem

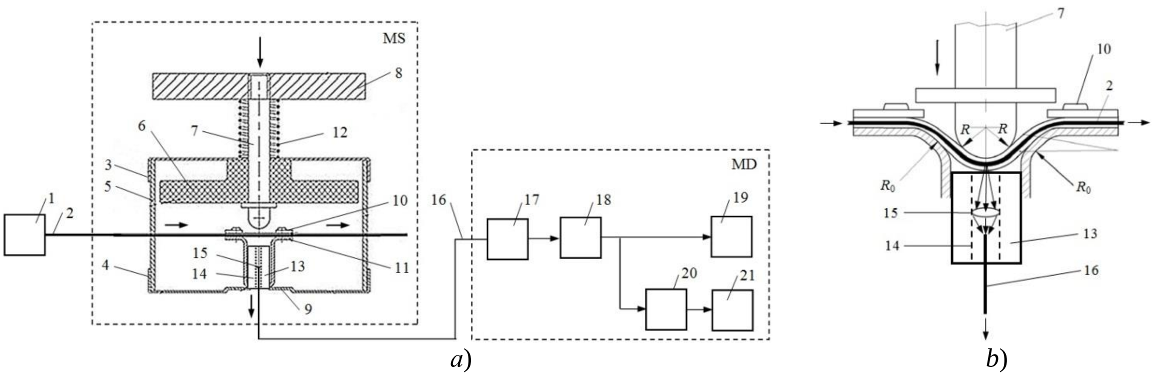
As is known [2-6, 8-11], the existing fiber-optic sensors allow detecting the fact of unauthorized access to the territory of the protected object, but cannot determine the mass of the object of unauthorized access. In this regard, there is a need to develop a fiber-optic sensor to ensure the functional security of the perimeter security system of an object, which makes it possible to determine not only the fact of unauthorized access, but also parameters, namely the mass of an unauthorized access object and conduct experimental studies on choosing the type of optical fiber as sensing element, the dependence of the attenuation of the optical radiation signal on the radius of the macrobend, the length of the arc of the macrobend and on the mass of the object.

In this case, functional safety is the safe operation of safety-related facilities and other means of risk reduction. In the event of a critical situation, the fiber optic sensor branches off the optical radiation signal, this signal is sent to the control panel and the system puts the equipment in a safe state. For the development of a fiber-optic sensor, an optical fiber of the G655 type with the highest susceptibility to macrobending was chosen. It has been established that an increase in the length of the macrobending arc at a constant radius leads to an increase in the attenuation of the optical radiation signal in the optical fiber [2].

The purpose of this work is to develop a fiber-optic sensor to ensure the functional security of the perimeter security system of an object, which would allow to determine not only the fact of penetration, but also the parameters, namely the mass of the object.

III. Development of a fiber optic sensor

Based on the analysis of the principles of construction of existing fiber optic sensors [2-6], a fiber optic sensor was developed to ensure the functional safety of the perimeter security system of an object with a macrobend shaper (FMI) of an optical fiber and a measuring device (MD), the schemes of which are shown in Fig.1 [1] .



a) *b*)

Fig. 1: *Scheme of a fiber optic sensor (a) and a macrobend shaper (b)*

Fiber optic sensor to ensure the functional security of the perimeter security system of the object consists of a source of optical radiation -1, the first optical fiber -2 with a core and a reflective coating, top -3 and bottom cover -4, casing -5, guide -6, movable rod -7, buttons -8, supports -9, strips -10, membranes -11, springs -12, fixed rod -13, funnel-shaped holes -14, lenses -15 placed in the funnel-shaped holes -14 and opposite the site with a macrobend, the second optical fiber -16 for transmitting a branched signal of optical radiation, a photodetector -17, an amplifier -18, a level meter -19, an electronic reporting device -20 that performs mathematical operations and an electronic indicator -21 (Fig. 1) [1].

The fiber optic sensor works as follows.

In the process of unauthorized entry into the protected object, when the button -8 is pressed by a body with a mass m, the movable rod -7 moves down along the guide -6 and is pressed against the membranes -11. The first optical fiber is laid between the membranes. To prevent the first optical fiber -2 from slipping to the sides during compression and creating a macrobend in the form of an arc of a circle, two low parallel guide rollers are placed in one of the membranes -11. The first optical fiber -2 is located between these rollers. This arrangement prevents sliding of the optical fiber -2 to the side in case of action on the membrane -11 of the movable rod -7, and when the action stops, it helps to straighten the first optical fiber. When the impact on the button -8 by a body with mass m -8 spring -12 opens, the movable rod -7 returns to its original position, and the first optical fiber -2 returns to a straight position. As a result of the action of the movable rod -7 on the membranes -11, the process of macrobending of the first optical fiber -2 occurs, the radius of which corresponds to the radius R of the round end of the movable rod -7 (see Fig. 2). With the help of the round end of the movable rod -7, a macrobend of the first optical fiber -2 with the corresponding radius R is formed, and from this macrobend the optical radiation branches off, which passes through the holes in the form of a funnel -14, the lens -15, placed in the hole in the form of a funnel, on the contrary a section with a macrobend and this radiation is focused by a lens onto the input of the second optical fiber -17, the input of which is located at the focal point of the lens -15. From the output of the second optical fiber -17 enters the input of the photodetector -16, which converts the branched optical radiation into an electrical signal, from the output of the photodetector to the input of the amplifier -18, from the output of the amplifier in parallel to the input of the level meter -19 and the electronic reporting device -20, which automatically performs mathematical operations, from the output of the electronic reporting device -20 to the input of the electronic indicator -21. The first optical fiber -2 together with the membranes -11 is attached to the supports -9, and the distance between them is equal to the diameter of the movable rod -7. The edges of supports -9 are made in the form of a round funnel with a radius R, which makes it possible to exclude attenuation of the branched optical radiation at the edges of supports -9 during macrobending (Fig. 1). The movable rod -7 rests on the shoulders of the supports -9, to limit its movement, the support -9 is used, which prevents the membranes -11 and the first optical fiber -2 from breaking in the event of a strong impact. When the button -8 of the fiber-optic sensor is exposed to any mass, the process of branching of the optical radiation transmitted by the source of optical radiation -1 along the first optical fiber, which passes through the lens -15, placed in the hole in the form of a funnel, opposite the area with a bend and the second optical fiber -16 is fed in parallel to the input of the level meter -19 and the electronic reporting device -20. The level meter -19 measures the attenuation of the branched optical radiation.

IV. Experimental setup and research methodology

Optical fibers G652, G655 and G657 are used in fiber optic communication lines, and also have different susceptibility to macrobending, i.e. the degree of response of the optical fiber to the appearance of a macrobend (a bend with a radius of more than 1.0 mm), therefore, studies were carried out on optical fibers G652, G655 and G657. To evaluate the response of an optical fiber to macrobending, parameter $\Delta\alpha / \Delta L$, is used where $\Delta\alpha -$ is the corresponding change in the attenuation of optical radiation, $\Delta L -$ is the change in the length of the macrobending arc. In this case, the attenuation of the optical radiation signal during propagation along the optical fiber is determined by the following formula [2-7]:

$$\alpha = 10\lg(P_{inp} / P_{out}), \tag{1}$$

where $P_{inp} -$ and $P_{вout} -$ are the power of optical radiation at the input and output of the optical fiber.

Block diagram of the experimental setup.

Fig.2 shows a setup for experimental studies, consisting of an optical radiation source (SOR), an optical radiation signal power meter (ORP), which are part of a verified and calibrated optical tester, and a macrobending shaper (MS). The source of optical radiation is connected to the optical power meter using an optical fiber. The shaper allows forming macrobends with a radius of 2.5…15 mm. Also, using the macrobend shaper, you can create a coil in the form of a circle and arcs of this circle [2].

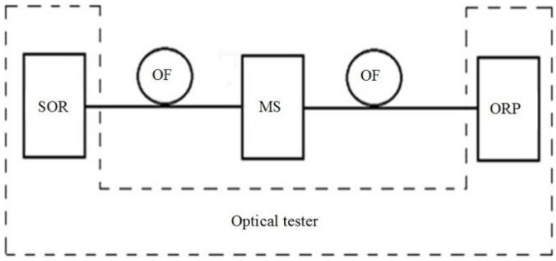


Fig. 2: *Scheme of the experimental setup*

The operating principle of the experimental setup is as follows.

An optical radiation signal with a power of 1.0 mW and a wavelength of 1310, 1490, 1550 and 1625 nm comes from the source of the optical radiation signal into the optical fiber, which corresponds to the transparency windows of the studied optical fibers (the optical power measurement range at these wavelengths is $10^{-11}...10^{-2}$ W). At a power of 1.0 mW, the instability of the optical radiation power does not exceed 0.005 dB. An optical radiation power meter is connected to the output of the optical fiber, and a macrobend shaper is placed on the optical fiber (Figure 2). The length of the optical fiber for the experiments was chosen to be small, 2.0 m, so that the attenuation of optical radiation in this optical fiber could be neglected in the absence of a macrobend.

For measurement, experiments were carried out in accordance with the requirements of the ISO / IEC 17025-2019 standard at an ambient temperature of 20-25 ° C, humidity up to 70% and atmospheric pressure of 975-1025 Pa. It is shown that the attenuation of an optical fiber is quite stable under these environmental parameters, and also under these conditions, the stability of the optical radiation source and the sensitivity of the optical radiation power meter remain constant.

V. Experimental results and discussion

To determine the susceptibility of an optical fiber to macrobending, the dependence of the attenuation of the optical radiation signal in the fiber α on the macrobend radius R was studied. Based on the results obtained, the dependences of α on R were plotted for the wavelength of the optical radiation signal λ=1490 nm for one full turn (1 - G657; 2 - G652; 3 - G655), which are shown in Fig.3.

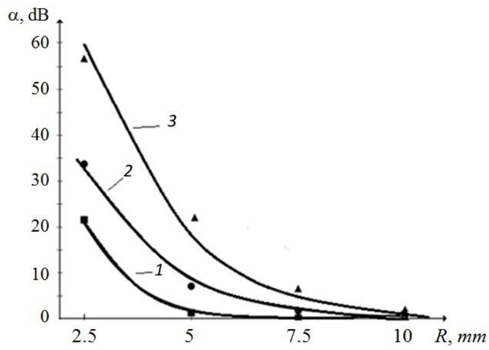


Fig. 3: *Dependence of attenuation on the macrobend radius of an optical fiber*

For other values of λ, the dependences were similar. In Table 1 shows the values of α at $R = 7,5$ mm for all types of optical fibers under study. As can be seen from Fig.3 and Table 1, the G655 optical fiber has the highest attenuation values in the entire R range under study, and therefore, this optical fiber is used further to develop a fiber-optic sensor.

Table 1: *Characteristics of the studied optical fibers*

Optical fiber	Optical radiation signal power attenuation at a macrobend (dB), at optical radiation wavelength, nm			
	1310 nm	1490 nm	1550 nm	1625 nm
G 652	0,5	2,0	2,6	5,5
G 655	3,5	5,4	7,5	9,6
G 657	0,2	0,5	1,2	3,3

Fig. 4 shows the dependence of the attenuation of optical radiation on the macrobending arc length L at a constant value of $R = 7,5$ mm for various wavelengths (▲ - λ=1625; ■ - 1550; ● - 1490; ♦ - 1310 nm). As can be seen from the results obtained, an increase in L leads to an increase in the attenuation of optical radiation. This dependence is close to a linear dependence and we can assume that [2]:

$$\alpha = \frac{\Delta\alpha}{\Delta L} \cdot L. \quad (2)$$

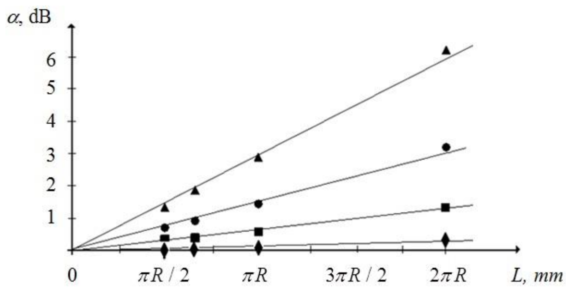


Fig. 4: *Dependence of the attenuation of the optical radiation signal on the length of the macrobending arc*

An increase in the wavelength of the optical radiation signal λ leads to an increase in $\Delta\alpha / \Delta L.$ Thus, for $\lambda = 1310$ nm, the value is $\Delta\alpha / \Delta L = 0,01$dB/mm; for 1490 nm - 0.04 dB / mm; for 1550nm - 0.10 dB / mm; for 1625nm - 0.21 dB / mm. With an increase in the macrobend radius R from 7.5 mm or more, a decrease in $\Delta\alpha / \Delta L$ was observed for all values of λ. It should be noted that at $R = 8,0$ mm only for $\lambda = 1310$ nm $\Delta\alpha / \Delta L = 0.$ $R \geq 15$ mm for all wavelengths of optical radiation $\Delta\alpha / \Delta L.$ At $R < 7,5$ mm, an increase of $\Delta\alpha / \Delta L$ was observed with a decrease of R for all values of λ. At $R < 2,5$ mm, the value of ratio $\Delta\alpha / \Delta L$ was not evaluated, since for such values of the macrobend radius R, a break in the optical fiber could occur. Note that at $R < 2,5$ mm and $L = 2\pi R$ mm, the macrobend attenuation of the optical fiber becomes quite large, $\alpha > 90$ dB for $\lambda = 1625$ nm.

In Table 2 shows the numerical values of ratio $\Delta\alpha / \Delta L,$ obtained for the optical radiation signal wavelength of 1550 nm and different macrobend radii of the G655 optical fiber.

Table 2: *Optical fiber macrobend characteristics*

R, mm	7.5	9.0	10.0
$\Delta\alpha/\Delta L$, dB/mm	0.07	0.06	0.02

From the data given in Table 2 it follows that a decrease in the radius of the macrobend R of the optical fiber leads to an increase in the ratio $\Delta\alpha / \Delta L$. The maximum value of the arc length L of the macrobend of the optical fiber, which is obtained when a penetrating object acts on the fiber optic sensor, is πR. The largest displacement of the rod Δx under the influence of the object of unauthorized access to the button depends on the value of the macrobend radius. The dependence of the length of the macrobending arc on the displacement of the rod under the influence of the unauthorized access object on the button has the following form [2]:

$$L = 2R \arccos\left(1 - \frac{\Delta x}{R}\right). \quad (3)$$

The displacement of the rod Δx will depend on the spring constant k and the mass of the penetrating object m, affecting the button of the fiber optic sensor:

$$\Delta x = (mg) / k, \quad (4)$$

where $g -$ is the free fall acceleration.

On the other hand, the relationship between damping Δa and mass m is given by:

$$\Delta a = (mg) / k, \quad (5)$$

Using expression (5), the relationship between the mass m, acting on the button of the fiber optic sensor and the resulting attenuation Δa, can be determined as follows:

$$m = (\Delta a \cdot k) / g. \quad (6)$$

After the value of the attenuation change Δa is known, at the output of the electronic reporting device -20, which performs mathematical operations according to expression (4), the value of the physical quantity proportional to the mass m of the unauthorized access object is obtained, which is transmitted to the input of the electronic indicator -21, the scale of which calibrated proportionally to the mass m. On the scale of the electronic indicator, a value proportional to the mass is obtained, which makes it possible to determine the mass of m, performing unauthorized access to the territory of the protected object.

Then the dependence of attenuation α on m mass of the object of unauthorized access has the following form:

$$\alpha = \frac{\Delta\alpha}{\Delta L} \cdot 2R \cdot \arccos\left(1 - \frac{mg}{kR}\right). \quad (7)$$

Thus, the relationship between optical attenuation and mass is a function of the inverse cosine. This function, described by expression (7), has a section where the relationship between α and m is close to linear. We will use this section of the dependence in a fiber-optic sensor to determine the mass by the value α.

For the used design of the fiber-optic sensor and spring, the experimental data on the attenuation of the optical radiation signal α from the mass m of the unauthorized access object are given in Table 3, and the dependence in Figure 5 for the wavelength of the optical radiation signal 1 is λ=1310; 2 - 1490; 3 - 1550; 4 - 1625 nm.

Based on the Table 3 of the data, the dependence of the attenuation of the optical radiation signal on the mass of the unauthorized access object is plotted, which is shown in Fig.5.

With a radius of the rounded end of the rod of 7.5 mm, it is possible to perform measurements α for all investigated wavelengths of optical radiation. As can be seen from the dependences obtained, in the range from 3.3 to 7.5 kg, the dependence of attenuation α on m is close to a linear dependence. For the sensor at $m < 3,3$ kg, the displacement of the rod was such that the length of the macrobending arc provided a small attenuation of the optical radiation signal and the error of the radiation power meter did not allow more accurate results to be obtained. Thus, this fiber optic sensor can be used to measure the mass of objects of unauthorized access.

Note that in a certain range of rod displacements, the dependence of α on Δx is also linear. Therefore, before starting the operation of the sensor, it is necessary to determine the $\Delta x -$ minimum value of this range. For example, for this you need to increase the mass of the button by 3.3 kg. Then the sensor will be able to measure the mass in the range of 0 to 4.2 kg.

Table 3: *Experimental data on the attenuation of the signal of optical radiation and the mass of the object of unauthorized access*

Optical fiber	Optical radiation signal power attenuation at the macrobend (dB), at optical radiation wavelength, nm							
	1310 nm		1490 nm		1550 nm		1625 nm	
	Weight, mm	Attenuation, dB	Weight, mm	Attenuation, dB	Weight, mm	Attenuation, dB	Weight, mm	Attenuation, dB
G655	1	0	1	0	1	0	1	0
	2	0	2	0	2	0	2	0.1
	3	0	3	0.1	3	0.4	3	0.9
	4	0.1	4	0.5	4	1.25	4	1.8
	5	0.2	5	1.0	5	2.25	5	3.15
	6	0.5	6	1.25	6	4.0	6	4.5
	7	0.75	7	1.6	7	5.4	7	6.0

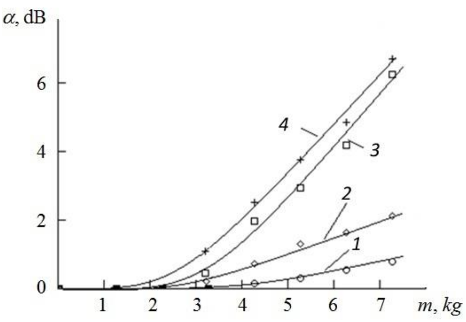


Fig. 5: *Relationship between optical attenuation and the mass of the penetrating object*

An increase in the wavelength of optical radiation leads to an increase in the sensitivity of the sensor. The sensitivity of the sensor is understood as the ratio of the value $\Delta\alpha$ to the corresponding change in body weight Δm. So, for the linear section of the dependence of α on m, the highest sensitivity corresponded to λ=1625 nm and amounted to 1.4 dB/kg, and the lowest for λ=1310 - 0.2 dB /kg.

Thus, experimental studies of a fiber-optic sensor based on the macrobend of an optical fiber showed the possibility of using it to measure the mass of a penetrating object on the perimeters of a protected object. In order for the sensor to measure a large mass, the spring rate must be increased. You can determine the spring constant for the required mass measuring range using the following formula [2,7]:

$$k = (m_{\max} g) / R, \tag{8}$$

where $m_{\max}$ – is the maximum mass.

Obviously, other designs of the mechanical part of the sensor can also be used, providing a displacement of the rod that forms the macrobend of the optical fiber by a distance of Δx proportional to the mass.

VI. Conclusion

Depending on the intensity of the branched signal of optical radiation, the developed fiber-optic sensor makes it possible to detect unauthorized access to the territory of a protected facility, to increase the measurement range of the attenuation of the branched signal of optical radiation by amplifying the branched signal of optical radiation and the limit of measuring the body weight of an object of unauthorized access by choosing the coefficient spring stiffness.

Experimental studies have shown the possibility of the developed fiber-optic sensor for measuring the mass of an object of unauthorized access to the perimeters of a protected object, and by choosing the spring stiffness coefficient, it is possible to increase the range of measuring the mass of objects.

Based on the experimental studies carried out, it was concluded that less than 50% of the intensity of the optical radiation signal source is obtained at the output of the fiber optic sensor and transmitted through the second optical fiber, and more than 50% at the direct output of the first optical fiber.

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