Some issues of developing fiber-optic systems for protection of distributed parameters

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Abstract. This article deals with the problem of ensuring protection of limited access objects and other objects of state significance from unauthorized access. There is given the analysis of systems already developed by Russian and foreign scientists. A passive perimeter security system is proposed for consideration the main element of which is an optical fiber. The measurement principle is based on controlling the magnitude of the additional dissipation losses under mechanical action measured in dB. There have been carried out field experiments using the proposed security system. In conclusion there are describes the results of the study using a reflectometer.

1. Introduction
At the end of the 20th century, optical fibers were actively introduced into the telecommunications sector as a guiding high-speed information transmission system; this is a worthy alternative to coaxial copper communication cables and radio-relay systems. Over more than half a century of industrial development of fiber-optic equipment and technologies, significant success has been achieved, which has allowed traducing many times the cost of optical fiber and equipment, while significantly improving their consumer qualities. Optical fiber is actively used not only in fiber-optic information transmission lines, but also in various information-measuring systems [1, 2]. Sensors based on optical technologies have several advantages over electric ones [3–7]. Accordingly, their scope is expanding annually. One of the aspects of using telecommunication optical fibers is protection of various objects and perimeters. Optical fiber (OF), which has a number of advantages, can be successfully used as a sensitive sensor and a communication cable with the operator panel. OF is energetically passive, has high electromagnetic noise immunity and corrosion resistance, and does not produce electromagnetic fields around itself, which makes it difficult to detect. Positive qualities provide their use in various fields of technology as sensors with high metrological characteristics, for example, as sensors of distributed systems for monitoring the technical condition of extended objects, as well as for their protection [8].

The analysis carried out shows a significant interest in the use of environmental agents in security systems. In the world market there are already security systems of various companies in the production
and sale. The first patent for security systems of this type was registered in the USA in 1977. This became the basis for subsequent developments. The basis is a radiation source, a fiber optic sensor, a photodetector and a data processing device. There are a number of successful developments and leaders in this field that have been in the market within several decades, for example, the Future Fiber Technologies FFT (Australia); the Remsdaq (England); the TRANS Security Systems and Technology (TSS) (Israel); the Fiber Sen Sys (USA); the Magal (Israel); the Senstar-Stellar (Canada). There are manufacturers who are just entering the market, and these are mainly countries of the former USSR, for example, the NGO Applied Radio Physics Voron (Russia); the Danube (Russia); the Gyurza (Russia). There can be noted individually the success of the developers of the Yangtze Optical Fiber and the Cable Company Ltd from China. Naturally, each manufacturer uses its own developments, methods and tools, but when analyzing available sources, since these developments are not adequately covered in the open press, and some are classified, we can conclude that there are a number of certain similarities between different security systems that combine them into several groups. There are more common characteristic similarities: the use of the principle of an optical interferometer. Each manufacturer seeks to improve the technical level of their products, but there are circumstances that cause a number of common problems that limit their applicability and lead to a serious price rise [9, 10]. For example, the use of the principles of an optical interferometer causes a number of problems in the event of interference due to thermal effects on the optical fiber. Therefore, the completely unsolved known problems of distributed fiber-optic security systems and the absence of available detailed information of their design serve as the basis for additional research and familiarization of the general public with the principles of their functioning.

The competitors of extended objects security systems are various systems in the market that record violations within the same security zone; there is also the need to organize a wired and wireless communication channel. There is a problem of signal attenuation in wired systems: energy supply of zone receiving and transmitting points; radiation of electromagnetic waves by security devices and ease of detection and suppression. There are security systems using the following fundamentals and methods: capacitive, vibration, radio wave, infrared systems, as well as video surveillance systems.

The developers apply a variety of methods for recording vibration effects on a fiber optic cable, for example, the Fiber Sen Sys intermode interference registration method by the FOIDS double-beam interferometry principle (the manufacturer is the Mason & Hanger, USA). There is another group of security systems that uses the Bragg grating effect and caused by it light reflection or scattering, which is captured by a sensitive photodetector. Security systems that use an optical reflectometer as a basis, work on a similar principle.

2. The theoretical part of the study

As it has been mentioned above, basically all security systems based on OF have three identical basic parts. As the light source, there is, as a rule, used a semiconductor laser, but a semiconductor diode can also be used. The sensitive sensor is a single-mode or a multimode fiber. The former is suitable for distributed perimeters of more than one kilometer, and the latter is more suitable for distances of less than one kilometer. Their combinations also occur when a multimode fiber is used as a sensor, and a single-mode fiber as a data transmission guide, for example, the Fiber Sen Sys uses this arrangement with the placement of a fiber-optic sensor on a mesh fence.

The sensor can be located in the ground at a shallow depth of about 5–8 cm. This arrangement is used by the Remsdaq (England). Combinations with placing the sensor on the fence and in the ground at the same time are also possible. The fiber-optic security system can be combined with other types of alerts about intruding into the protected area, for example, with video surveillance.

For convenience, the description of the basis of these security systems can be used in the classical theory of optical interferometer. The theoretical basis for the operation of this device is known and is the sum of adding two light waves $E_1$ and $E_2$. It is manifested in changing the resulting intensity $I$ that is recorded by the photodetector device of the interferometer. As it is seen in Figure 1, there occurs mechanical microbending of the fiber, which leads to changing the properties of light (the mode) passing...
through it, and the refractive indices $\Delta n$ accordingly change. Changing the propagating phase of the light wave $\Delta \phi \sim \Delta n$ plus changing the vector of the electromagnetic field of the wave $E$ affecting polarization is recorded by the interferometer.

![Image](image.png)

**Figure 1.** Changing the light wave phase under mechanical action.

Based on the well-known theory of optical interferometer, we compose an expression for two coherent light waves, relating the change in intensity $I(t)$:

$$I(t) = E_1 E_2 \cos [\Delta \phi + \Delta \phi(t)],$$

(1)

where $t$ is the time; $\Delta \phi$ is the initial and having random nature difference of phases of interfering light waves; $\Delta \phi(t)$ is the difference of phases related to changing the conditions of propagation in the optic fiber under the external mechanical action and fiber deformation.

3. Developing designs of fiber optic systems for protection of perimeters

There are proposed two designs that can be used to build fiber-optic security systems. They are presented in Figures 2 and 3. There are certain fundamental differences between them that can determine their scope in security systems. The presented design in Figure 2 is technically more complex and more expensive. It implements the method of coherent optical reflectometry with time resolution, uses the principles of the C-OTDR (Coherent Optical Time Domain Reflectometry) technology. Optical fibers are connected to the analyzer using connectors. Through the optical branch, the laser beam is divided into $n_x$ number of rays. At this, the semiconductor laser operates in the pulsed mode. An important role is given to the optical switch that switches the fiber from the radiation source to the photodetector within micro- or nano-seconds, depending on the length of the protected perimeter. The known effect of optical scattering arises, and part of the optical radiation is reflected back from various kinds of inhomogeneities. In various situations, scattering is not the same in value and, accordingly, under mechanical action on the optical fiber there occurs microbending, and it increases in value. Figure 2 shows the direction of the direct light pulse and the one reflected from the inhomogeneity.

The fiber optic sensor is connected to the optical switch via optical connectors to the communication cable. This circumstance allows estimating the magnitude of the impact and to determine accurately the distance to the point of impact. Accordingly, it is possible to identify the characteristic factors of violation of the protected perimeter. This design is presented in a multi-channel version and can be used to protect several sections simultaneously, using one data center that processes the received reflectograms and, when deviating from the basic reflectogram, gives an alarm. The specified system based on calculating the delay time of the reflected signal is able to determine the location of the invasion from 30 to 50 meters. It all depends on the technical level of the equipment used. The method will determine the location of the invasion. The reflected light first goes to the photodetector, then it is pre-processed and converted to an electrical signal, then the analyzer analyzes the reflectograms with the
existing base of reflectograms of the protected area. Then, through the matching device, the information enters the computer, where it is visualized using software. The efficiency of the system increases significantly if regular inhomogeneities of the refractive index are specially developed in the fiber with a spatial period comparable to the wavelength of laser radiation. It is necessary to form the conditions for Bragg scattering.

![Diagram](image)

**Figure 2.** Design of fiber optic systems for protection of perimeters based on coherent optic reflectometry with time resolution.

Taking into account these circumstances, a more simplified version of the fiber-optic system has been developed, which is shown in Figure 3. In contrast to the previously considered design, there is no optical switch with a control system, which greatly simplifies and cheapens the security system. As before, a semiconductor laser with the power of 10–30 mW with an optical splitter is used as a light source. The radiation power is evenly distributed between the channels, which should be at least two. For example, it is possible to divide the perimeter into 8, 16, 32 and 64 zones, where a certain protected area of 10–30 meters long and up to 3 meters wide is formed. The light passes through the optical fiber and enters the photodetector, which captures its change. Under mechanical action or vibration, there occurs changing the properties of light and occur the values of additional losses, which is the basis for operation of the security system. Otherwise, the analyzer, the matching device, and the personal computer perform the same functions as in the design discussed earlier in Figure 2. The design of the fiber optic perimeter protection system based on the control of additional losses is shown in Figure 3.
Figure 3. Design of fiber optic systems for protection of perimeters based on controlling additional losses in the OF.

This design can be used both in the terrain and in the underground version of the fiber-optic sensors dislocation. If we divide the protected perimeter into certain zones, then we can develop a multi-channel security system that is significantly less expensive and more complex. The proposed design has also partially the drawbacks of the previously discussed ones, for example, if you cut the sensor in several places, the area fails, but the alarm still arrives at the operator’s console, since the areas are relatively small in length: from 10 to 50 meters, and if necessary up to 100–500 meters, then intrusion detection will be quite effective. In this design cable reservation can be applied. The sensor uses a 9/125 μm (OS2) Corning SMF-28e + ® single-mode optical fiber with a low "water peak" (ITU-T G.652 standard), in a wired silicone sheath with the diameter of 1 mm. For communication with sensors, a standard telecommunication multi-fiber gel-filled cable for external laying is used, with single-mode fibers, the G.652 standard, up to 120 fibers. At the points where the sensor and the communication cable are connected, a connecting optical module is mounted. The communication cable is immersed to the depth of 0.7 – 1 meter and is equipped with intrusion protection, free fibers being used for this.

In practice, the design shown in Figure 4 is implemented as follows. From the coherent radiation source, which is semiconductor laser 1, through optical splitter 2, light is supplied through the OF of communication cable 3 to each of zones from I to Nx, within 60 channels. Each channel requires two OFs. To separate the fibers into zones, junction boxes 4 are used. Fiber-optic sensors 5 are connected to each pair of OFs of the communication cable through optical connectors 5. The light transmitted through the sensor is returned through the return fiber and gets to photodetector 6, then light waves are converted into an electrical signal in processing device 7. Computer 8 is used for data processing, as well as storage and visualization of the information. Sensors can be located on the fence or on the plastic mesh in a shallow trench (Figure 4).
Figure 4. Simplified design of fiber optic systems for protection of perimeters based on controlling additional losses in the OF with locating sensors in zones.

Under any mechanical action on the fence and, accordingly, on the sensor, the properties of the light passing through the sensor change, additional losses and a change in the headlights of the light wave occur, which is captured by the photodetector. Next, the microprocessor device produces the received data and issues a decision on the operation of the system. An important point is the development of software that allows effective dealing with interference.

Figure 5 shows photographs of a laboratory sample of the security system and pictures of diffraction light spots, which can vary depending on various types of vibrational and mechanical actions on the fiber-optic sensor. The assembled library of spots allows using computer programs to compare changing the received light spots with the original ones and, with its corresponding change, give an alarm. According to its operating principle and construction, this design is similar to that considered earlier in Figure 3. Its difference is that a television matrix is used as a photodetector, to which a light spot arriving from the sensor is supplied. Accordingly, the image of the spot is transmitted to a personal computer, where it is processed using software.

Figure 5. Laboratory bench of the fiber optic systems for protection perimeters based on changing the light properties and controlling additional losses in the OF.

Under the action on the fiber, the aperture of the transmitted light changes, the diffraction pattern changes, which is recorded by the matrix sensitive to such changes. The fiber-optic sensor has a fairly high sensitivity, changes with any vibration exposure in the frequency range from 1 Hz to 200 kHz, as well as with direct contact with the sensor in case of microbending. The experiments show that the
security system clearly responds to all zones, both with a separate effect on the sensor and with simultaneous exposure to several sensors. False triggering due to various interference is provided through software with a mandatory temperature correction.

For clarity of observing the changes in light spots there was used the visible range of laser radiation of 650 nm, but experiments were also carried out with the invisible range of radiation used in telecommunications: 1310 and 1550 nm. This range provides a significant remoteness of the sensors, within 10 – 50 km, from the location of the operator’s console.

Also, when conducting the study, the methods of analysis proposed by Russian authors were used [11].

4. Conclusions
1. All the presented designs with the underground arrangement of fiber-optic sensors have high stealth and difficulty in detection, since the sensors are immune to electromagnetic and radio-frequency interference.

2. With the development of the time-resolved coherent optical reflectometry technology using a single-mode fiber as a sensor and a guiding communication system, it is necessary to develop effective methods of protection against interference and temperature correction, as well as cable armoring, which makes it possible to organize very extended security zones (up to 60...100 km) with intrusion detection accuracy up to several meters.

3. With the open laying of fiber-optic sensors on fences, it is necessary to armor the cable to prevent its intentional damage in several places, which leads to a complete and long-term system failure.

4. The experiments carried out show that in a pulsed mode of operation of the radiation source, the use of a multimode fiber as a sensor is more noise-immune at temperature changes than a single-mode fiber. It is recommended to use a multimode sensor up to 1 km long and a single-mode fiber for communication with the security system remote control.

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