Passive Perimeter Security Systems Based on Optical Fibers of G 652 Standard

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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

Ensuring the protection of limited access and hazardous objects of state importance or just private territories that occupy large areas from unauthorized access, in contrast to local objects, requires large expenditures and complex communication to build a perimeter security system and monitoring. This fact increases significantly the cost of security systems. Today a lot of security systems of different technical levels and costs have been developed that are based on different principles: infrared, vibro-acoustic, magnetometric, capacitive, seismic and other types of systems [1-7]. Perimeter security systems monitor continuously the area of space along the protected boundary by some active physical parameter (physical field). When it is violated and the parameters go beyond the permissible, an alarm is triggered that is sent to the information collecting and processing system. All the systems can be divided into active and passive. The former are more expensive and can be detected by the intruder before they are triggered. Such devices require supplying electrical power, as well as a communication line for transmitting signals or a wireless data system over the air [1-4]. Special tools can be used that bring them out of action. Passive systems are less costly, and in contrast to the active ones are secretive. For example, scientists from Novosibirsk developed a passive perimeter security system using seismic acoustic sensors (geophones) [8-14]. Passive systems control changes in the physical field of the environment and the soil oscillations, the parameters of which are generally random, but there is no radiation of energy into the surrounding space, which complicates their detection.

These systems have many advantages, but they also have disadvantages. For example, signal processing requires complex algorithms and devices, since otherwise false alarms and inaccurate parameters may be found in detecting the intruder. These systems provide absolute secrecy, since their principle of operation is passive, seismic sensors and connecting wires are usually immersed in the ground. When spreading over large areas or boundaries, this method is very complex and costly, since first of all there takes place attenuation of the electrical signal, and there are difficulties in their interaction with each other in the group based on the data obtained.

Based on the above-said, we propose to consider a passive perimeter security system that has all the advantages of a system with seismic acoustic sensors (geophones), but differs in the principle of operation, while not being inferior in technical parameters of work and less complex in configuration. An important difference is its lower cost. The basis for developing the system was the work aimed at monitoring and measuring in real time the deformation parameters of building objects (foundations, pipelines, bridge construction elements, etc.). Similar developments are underway in the field of mining, to monitor and control the deformation of mine workings, to protect personnel from the sudden collapse of the mine [15–16]. These systems are based on the use of optical fiber in communication systems for information transfer. The measurement principle is based on controlling the magnitude of the additional dissipation losses under mechanical action measured in dB. During mechanical action on the optical fiber, the energy dissipation indicators of the light electromagnetic wave mode passing through the optical fiber change. Considerable work has been done in this field, a number of experiments have been carried out and the original results obtained. Using an optical fiber, it is possible to measure a variety of electrical and non-electrical parameters in parallel with fairly high accuracy [11]. The annual reducing of the cost of optical fiber in the market and increasing its consumer properties, for example, in terms of transparency windows, make it very attractive for using in perimeter security systems. Today one km of a single-mode optical fiber can be bought for about $9, which makes it out of competition with a copper couple that is used for communication with seismic sensors (geophones), since the cost of copper wire in the market is very high. Electromagnetic interference does not affect an optical fiber. Therefore, the use of optical fibers to build passive systems for protecting the perimeters and borders of various objects is an extremely promising trend.

The main idea of the work is connected with the use of telecommunication optical fibers of the G 652 standard as a sensitive sensor capable of identifying mechanical effects. In this case an optical fiber is used as a sensor and a guiding system for transmitting information. All the obtained measurements in the form of a modified optical signal are processed by a microprocessor device, after which it is possible to identify impacts and to determine the distance to the point of the alleged violation of the protected perimeter.

2 METHODOLOGY OF CARRYING OUT FIELD STUDIES

The system development requires a series of studies based on the systemic approach. It is necessary to carry out computer simulations and field experiments to study the processes associated with the light propagation in an optical fiber and caused by mechanical strain deformations. The estimation of losses in the object under study is associated with developing deterministic models that reflect the physical essence of phenomena and contain a description of the mechanisms of the elementary processes taking place in them. The structural diagram of the developed system is presented in Figure 1.

The object of study is represented by an optical single-mode fiber of the G.652 standard that has low losses in the region of the hydroxyl peak (1383 nm), which makes it possible to use CWDM technologies more widely during transmission.

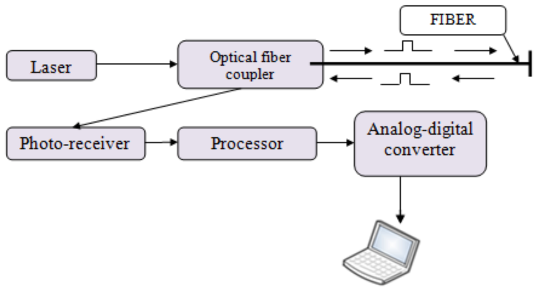

Figure 1: Structural diagram of the system developed.

The system we developed was compiled and tested. It consists of a laser, an optical coupler, a fiber, a photodetector, a microprocessor, and a laptop with software. We use a semiconductor laser as a radiation source. An optical receiving module is mounted at the output of the fiber, which makes it possible to estimate the loss value with accuracy of 10-3 dB. It is known that during mechanical deformations or vibrations in an optical fiber, the conditions for the light propagation or its internal reflection (dissipation) change, as a result of which the phase and spatial characteristics of the beam at the cable output undergo changes. The resulting changes will be recorded by the photodetector and processed by the signal analyzer. Preliminary experiments show that the light at the output of the optical fiber has a “spectrum” structure, this is an irregular system of light and dark spots, and under a mechanical effect on the optical fiber the “spectrum” structure changes (Figure 2). To fix these changes it is necessary to use space-sensitive photo-receivers.

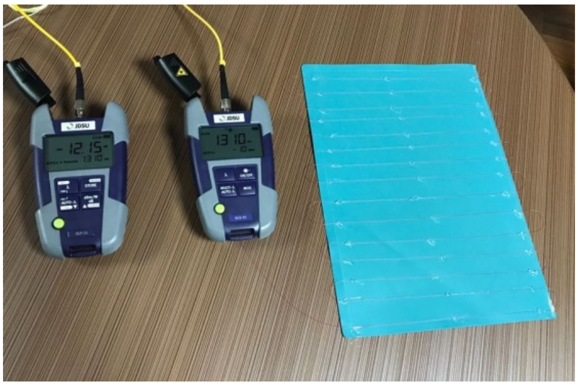

Figure 2: A laboratory test bench for practical approbation of the study theoretical results.

Our task is to develop a security system with the length of one zone up to 100 km with accuracy of detecting an intrusion site up to ±10 m. The depth of the optical cable is from 5 to 50 cm, the width of the sensitive zone is up to 4-5 meters. Under the effect of mechanical vibrations the optical fiber cables give a response in the frequency range from 1 Hz to 100 kHz; in the future for the security system it is planned to limit the frequency range from 100 Hz to 10 kHz.

The optical cable is attached to the plastic grid to increase the system sensitivity and the probability of detecting an intruder or group of violators on the ground, who can walk or run. We use the method of the correlation processing of signals from two fiber-optic cables, which allows isolating the signals of real intrusion from their background to filter out the noise. Three systems will be involved in the studies.

The first one is based on the use of the micro-stress method of mechanical action on an optical fiber and will use two optical fibers in which the laser beam passes (Figure 3). At the end of the zone we perform the interference of both beams in a special optical module. If a mechanical effect is exerted on the cable, the nature of radiation propagation in both fibers changes, and the dynamics of the interference pattern in the optical module allows registering an invasion.

The second system is based on the use of the classical Mach-Zander interferometer (Figure 4). The sensor has already three optical fibers. Two fibers are used as sensing elements, a laser beam operating in continuous mode is fed through them, and the third (output) fiber is used to transmit signals to the system analyzer from the terminal optical module. The radiation source is located in the analyzer unit, from which laser radiation is passed in the passive fiber to the initial module. In this module radiation is split into two beams that are fed to two sensitive fibers.

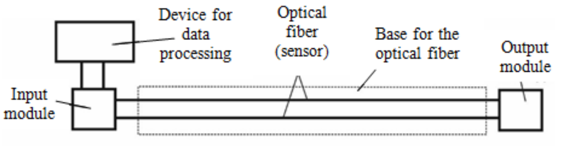

Figure 3: Structural diagram of the method based on the use of micro-stresses of mechanical action on the optical fiber.

In the terminal module both beams interfere. If both arms of this interferometer are in the unperturbed state, then the interference pattern in the terminal module remains unchanged. At this, the signal transmitted from the terminal module via the output optical fiber to the analyzer does not have a variable component. With the cable deformations or vibrations the optical path difference in the sensitive fibers (i.e., the interferometer arms) changes and the terminal module registers the variable component of the signal transmitting it to the analyzer. A specific feature of this interference system is that it determines the relative time delay of the recorded signals in both arms of the interferometer. This allows determining the location of the system invasion with accuracy of several meters.

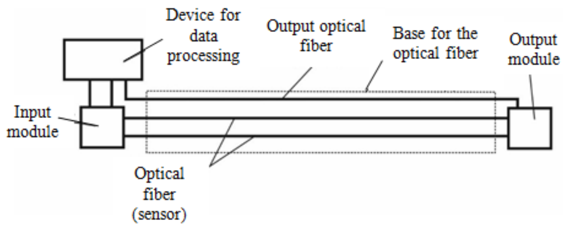

Figure 4: Structural diagram of the interference system.

The third system is based on the use of the method of coherent optical reflectometry with the time resolution (Figure 5). To the controller there are connected optical light guides that pass a laser beam. There takes place the known dissipation effect and part of optical radiation is reflected back from various irregularities. When the fiber optic light guide is subjected to mechanical stress (vibration), an alarm signal can be registered by the parameters of reflected optical radiation to trigger the system. The effectiveness of the system is significantly increased if regular refractive index irregularities with a spatial period comparable to the laser radiation wavelength are specially developed in the fiber. It is necessary to develop the conditions for Bragg dissipation. This method will allow determining the location of the invasion based on the calculation of the reflected signal delay time. It is possible to establish accurately the location of the invasion with an error of up to 10 meters.

To implement this system, it is necessary to lay not less than two fiber-optic light guides using the underground method to the depth of about 7-10 cm along the protected perimeter. The fibers must be attached to a plastic grid to increase the system accuracy and sensitivity. The correlation processing of signals from two fiber optic cables allows filtering out interference signals (noise of rain, traffic, etc.) and highlighting the signals of real intrusion on their background. This system can be used to protect and to monitor the integrity of pipelines. It is possible to configure the system using a closed loop, when both ends are connected to electronic units. When a sensor breaks, the system switches to the operation mode with two separate beams signaling the location of the cable break. At this, the operation is maintained throughout the entire perimeter. Separate conductors of standard fiber communication cables with optical losses of approximately 0.3 dB/km at the wavelength of 1550 nm are used as sensitive elements.

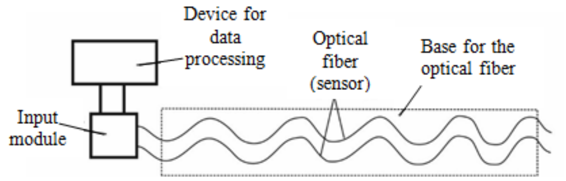

Figure 5: Structural diagram of the system based on the use of coherent optical reflectometry.

3 THE NUMERICAL SIMULATION RESULTS

Using a laboratory test bench, experiments were carried out to determine the loss of optical fiber at various pressures.

The numerical study of the VOD system model was carried out using the Wolframalpha program that is an interactive system for processing the results of experiments focused on working with the data files [8].

The boundary conditions are as follows: the energy of pressure on the fiber is from 0 to 15 Nm, the interval of the step is 2.4 Nm, total 7 steps, the temperature in the laboratory is 23 °C. The movement along the axes until pressure is applied: OX = 0m; OY = 0m; OZ = 0m. As a result of automated data approximation there were obtained the single-factor mathematical models.

Optical fibers with the wavelength of 1310 and 1550 Nm were studies. A plot of the optical fiber with the wavelength of 1310 Nm loss with the incremental pressure increase is presented in Figure 6.

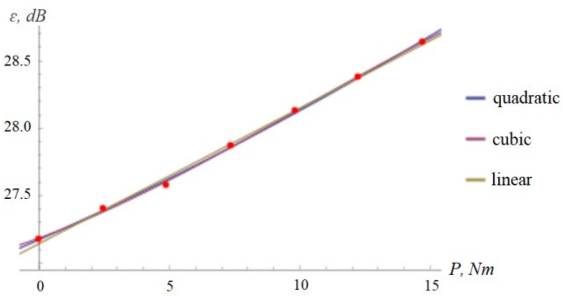

Figure 6: Loss values in the optical fiber with the wavelength of 1310 Nm with the step increment of pressure.

When performing an automatic approximation, the following results were obtained:

1) $0.000124408P^3 + 0.00373935P^2 + 0.0707259P + 27.1854 = \varepsilon$ is the third degree approximation (cubic);

2) $0.100308P + 27.1445 = \varepsilon$ the approximation is linear;

3) $0.000994195P^2 + 0.0856824P + 27.1744 = \varepsilon$ is the second degree approximation (quadratic).

Since the best mathematical model is considered to be the model with the lowest value of the AIC (Akaike Information Criterion), the dependence of the loss values in an optical fiber is better represented by a quadratic approximation.

A plot of the optical fiber with the wavelength of 1550 nm with step-by-step pressure increment loss is presented in Figure 7.

Evaluating the results we can conclude that the loss values in the optical fiber dependence is better represented by the quadratic approximation: $0.00195471P^2 + 0.256042P + 24.1281 = \varepsilon$.

To determine the distance to the place of violation of the perimeter security, the YOKOGAWA AQ1200 OTDR reflectometer was used. On the traces (Figure 8) it is clearly seen in which part of the optical fiber the loss changes.

On the trace it is shown that in the range of 0.411273-0.43224 km the return loss of the optical fiber is 0.334 dB, which indicates that pressure on the optical fiber in this interval is above the norm.

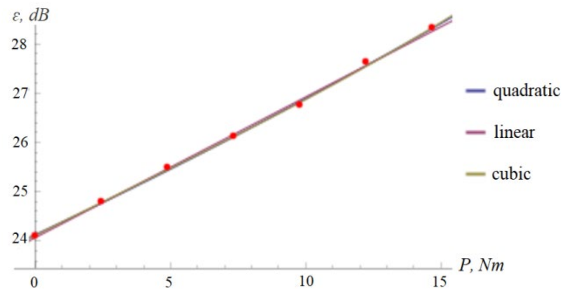

Figure 7: Loss values in the optical fiber with the wavelength of 1550 Nm with the step increment of pressure.

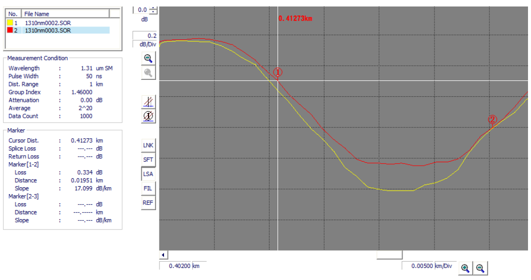

Figure 8: A fiber trace.

Based on our analytical and practical studies, we can draw a number of conclusions on the advantages and disadvantages of these systems. The advantages include the difficulty in detecting fiber-optic sensors (visually or technically), since the sensors are not susceptible to electromagnetic and radio frequency interference, a significant area of the protected perimeter is up to 60...100 km long with the intrusion detection accuracy of up to several meters. The disadvantages include a high cost of the equipment, complexity of setup, a number of preparatory measures for trenching, the need to fulfill certain conditions that ensure reliable system operation with optimal performance, the system planning and mounting the sensors. There is a probability that the system may give a false alarm, as it is sensitive to soil vibrations and seismic signals caused by passing nearby vehicles, large trees, railways, objects under construction. If these factors are present, then the sensors must be placed in shallow trenches filled with small gravel within the "forbidden" zone between two parallel fences, which allows partial isolating the sensors from the effects of these ground seismic effects. It is not recommended to mount the sensors directly into the ground, since a change in soil compaction and its movement can change significantly the system sensitivity and reduce the probability of an intruder being detected. When the sensors are laid directly in the grass, their sensitivity is greatly reduced, an intruder can be detected only when it strikes a fiber-optic light guide. A trench in which fiber-optic sensors are laid must be provided with a drainage system to drain water. The presence of water can lead to freezing at low temperatures (in winter), which will cause decreasing the system sensitivity. Soil erosion can cause the exposure of underground sensors or their immersion to the depth, and this will reduce the system sensitivity or make it completely inoperable.

4 CONCLUSIONS

As a result of the study the experiments were carried out with an optical fiber with the wavelength of 1310 Nm and 1550 Nm using a reflectometer to determine the location of violating the integrity of the protected perimeter. Using the reflectometer it was found that in the tested range of 0.411273-0.43224 km, the return losses of the optical fiber were 0.334 dB, which indicates that pressure on the optical fiber in this interval was higher than normal. In the future, a hardware-software complex will be developed that will make it possible to estimate automatically the obtained parameters of the protection section and to fix violations when the trace curve changes from the specified reference one. The signal will be transmitted automatically to the operator.

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