Investigation of additional losses in optical fibers under mechanical action

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Abstract. The relevance using of high-performance information and measurement systems based on fiber optic sensors to create systems for monitoring the geotechnical state of the rock mass is an extremely promising issue. This is a new generation of high-speed measurement monitoring systems that are able to function effectively in conditions that are dangerous due to a sudden explosion of methane gas as they do not transmit electrical signals and underground mines are one of the most difficult and tough environments for people's work. The authors substantiate the idea of using the optical fiber of the ITU-T G.652.D standard to create systems for monitoring the geotechnical state of a rock mass since the fiber-optic sensors developed on its basis have a sufficiently high accuracy, measurement speed and have a good linearity of characteristics. For testing control methods and measurement of geotechnical parameters of output the imitation laboratory standing on the basis of fiber-optical sensors was developed. Quartz single-mode optical fiber 9/125 µm (OS2) Corning SMF-28e+® was used. The authors conducted a series of experiments to study additional losses due to mechanical action on optical fiber.

1. Introduction

Safety of mining operations is an important aspect and priority of the complex mine system.

The first stage of development of information-measuring system based on fiber-optic sensors (IIS FOS) is an analytical study of existing achievements in this area based on a systematic approach and the solution of the problem as a whole. The results of the literature analysis are allowed to use the accumulated experience for the development of information-measuring system based on fiber-optic sensors that can work effectively in mines dangerous for sudden release of methane and dust.

During the operation of optical cables there are certain technical aspects associated with the occurrence of mechanical loads that can lead to bending of the optical waveguide which in turn causes signal attenuation and additional losses.

Laying fiber-optic communication lines there are often situations associated with the influence of external influences that affect the technical characteristics of the optical cable and the bandwidth of the telecommunication channel. The most important fact as practice has shown is the influence of the bending parameters of optical fibers and the occurrence of additional losses in the radiation power of the signal source in the optical cable.

These losses are especially high at such a bending radius, which is critical when the fiber conductor is on the verge of mechanical damage. This critical radius can be very small (only a few millimeters)
for fibers with a high numerical aperture, while the allowable bending radius is much larger (often tens of centimeters) for fibers in single-mode mode with a large cross-mode area.

It was completed the scientific analysis of similar works of foreign authors who work with optical fiber and develop fiber-optic sensors [1–3].

This is a new generation of high-speed measurement monitoring systems that are able to function effectively in conditions that are dangerous due to a sudden explosion of methane gas, as they do not transmit electrical signals, and underground mines are one of the most difficult and tough environments for people's work. Safety of mining operations is an important aspect and priority of the complex system of the mine.

The principal difference between the idea and existing analogues in the world is the integration of functions in one device with the possibility of automated monitoring, in real-time technical condition of mine workings on the basis of fiber-optic sensors (FOS) with which a multifunctional measurement system with high metrological accuracy. This system based on optical fiber provides wireless transmission of information from the sensors to the module of the automated control system has no analogues. A fiber-optic sensor is used which is a small device in size and allows detecting changes in various values of electrical and non-electrical parameters, which allows real-time tracking of deviations of the object under study.

2. **Laboratory tests**

For working out of methods of control and measurement of geotechnical parameters of developments the imitation laboratory stand on the basis of fiber-optical sensors which is presented in Figure 1 was developed.

Quartz single-mode optical fiber 9/125 µm (OS2) Corning SMF-28e+® with low "water peak" (ITU-t standard-652) was used.(D). It is not desirable to use fiber with Ultra series as it has a lower sensitivity to bending. The fiber has a primary coating of 245 microns (with an outer shell). To determine the values of optical radiation power and losses the VIAVI optical power meter (JDSU) SmartPocket OLP-38 was used. It operates in the dynamic range from -50 to +26 dBm with a wavelength range of 780-1650 nm. As a radiation source was used SmartPocket OLS-34/35/36 with built in options Auto-λ and Multi-λ, SmartPocket OLP-38 can automatically measure the power level and insertion loss in single-mode and multimode fiber optic cable. The connection to the optical fiber was carried out using a universal 2.5 mm UPP adapter and optical connectors FC.

The length of the compensation coil is 2 km of optical fiber (ITU-t standard 652.(D)).

![Image of laboratory stand](image.png)

**Figure 1.** Simulation laboratory stand.
With the help of the developed laboratory stand, a number of experiments were carried out to determine the optical fiber losses at different pressure values. Quartz single-mode optical fiber 9/125 µm (OS2) Corning SMF-28e+® was used. Also, modeling and calculation were performed with the help of finite element analysis in ANSYSv18 program. The General view of the model is shown in Figure 2.

![General view of the model](image)

**Figure 2.** General view of the model performed in the ANSYSv18 software environment.

The frame structure is under the pressure created by the rock. The calculation is carried out in 10 steps, at each subsequent step the pressure increases by 1 MPa, taking the initial value of 1 MPa and the final -10 MPa.

Fiber optic sensors have a number of advantages: the possibility of multiplexing, remote measurement, resistance to electromagnetic interference, the lack of electricity at the point of measurement, long-term stability.

We present a number of technical advantages of FOS in relation to traditional electronic systems of measurement and monitoring, through which FOS is planned to be used in mining IMS:

- safe use in explosive environment, complete intrinsic safety;
- elasticity with a minimum bending radius of 2 mm;
- wide signal bandwidth and the ability to multiplex signals;
- low weight and overall dimensions, high reliability and corrosion resistance;
- excellent parameters of noise immunity and non-inductance of channels, low energy costs for operation [4–6].

### 3. Full-scale modeling

With the help of the developed laboratory stand, a number of experiments were carried out to determine the optical fiber losses at different pressure values. When exposed to the fiber optic meter changes the output form of the light spot.

The numerical aperture (NA) is the sinus of the maximum angle of incidence of the light beam at the fiber end, at which the condition of total internal reflection is fulfilled. This parameter determines the number of modes propagating in the optical fiber [7–9]. Also, the value of the numerical aperture affects the accuracy with which the optical fibers should be docked with each other and with other components of the line. Figure 3 shows a diagram of the change in the deformation of the light spot forms.

![Diagram of deformation change in the shape of a light spot](image)

**Figure 3.** Diagram of deformation change in the shape of a light spot.
The aperture before and after the application of pressure on the optical fiber can be seen in Figure 4, which presents a diagram of the deformation change in the shape of the light spot. The camera captures the change in the shape of the spot and transmits the information to the computer where the program compares with the samples.

**Figure 4.** Aperture before and after applying pressure to the optical fiber.

The aperture shows that when the optical cable is deformed the light spot changes its shape. The value of additional losses and optical refractive indices in the optical fiber depends on the level of mechanical action and temperature which can be expressed through the following dependence:

\[
\frac{\Delta q}{q} = \frac{1}{q} \left( \frac{dq}{dT} \right) k + \frac{\delta q}{q}
\]

where

- \( q \) – additional loss of the optical fiber;
- \( \Delta q \) – change of additional losses;
- \( \left( \frac{dq}{dT} \right) k \) – is a partial derivative of the temperature dependence of optical fiber losses;
- \( \delta q/q \) – is the variation of additional losses due to the photoelasticity method.

\( \frac{1}{q} \left( \frac{dq}{dT} \right) \) the first part of the equation takes into account the changes in the additional losses arising in the optical fiber under mechanical action, and part \( \frac{\delta q}{q} \) the photoelasticity effect due to fiber deformation [10–14].

Change of additional losses due to photoelasticity \( \delta q \). We use the famous formula using coefficients of Pockels R:

\[
\delta q = -q^2/2 (\rho_{11} \cdot \sigma_1 + \rho_{21} \cdot \sigma_2 + \rho_{12} \cdot \sigma_z),
\]

where \( \sigma_1 \) and \( \sigma_2 \) – the value of the relative deformation occurring in the cross section of the optical fiber;

- \( \sigma_z \) – the value of the relative deformation occurring in the cross section d along the fiber axis;

\[
\sigma_z = \Delta l/l,
\]

where \( \Delta l/l \) – change in the length of the fiber segment with length l.

\[
\sigma_1 = \sigma_2 = -\nu \cdot \sigma_z.
\]

where \( \nu \) - is the value of the Poisson's ratio.

To register the excess of a given level of deformation, and hence the appearance of additional losses during deformation of the rock mass and the structure of the shaft support within 0.5%, a certain value of the change in the refractive index and the change in the cross section of the optical fiber, namely its core, due to a slight deformation due to photoelasticity equal to \( \delta q=9.6 \cdot 10^{-4} \). With the known speed of propagation of the optical signal:

\[
V = c/n,
\]

where \( c \) – is the propagation velocity of the optical signal in the fiber core;

- \( s \) – speed of light in vacuum;

\( n \) – is the refractive index of the optical fiber core.
If you take the length of the optical fiber used for measurement, conditional length of 1 km, with the deformation within 0.5%, will cause a change in the optical signal delay. For example if the length of the measuring transducer section is \( l = 1 \) km, then due to the deformation of 0.3%, the change in the optical signal delay in this section will be about 3 NS. By increasing the length of the control measurement area using a fiber-optic light guide with a length of 5 km with the already self-oscillating mode of operation can be 5 µs. This allows you to get the difference in the accumulation of pulses. The pulse accumulation time is 30 seconds. The change in the delay time in the optical fiber within 0.16 NS will be allowed to obtain a difference in the number of accumulated pulses equal to 2.

To increase the sensitivity of the measurement system, it is possible to increase the length of the optical fiber and the pulse accumulation time. The dynamic range of the strain measurement system will depend on: the sensitivity of the photodetector the power of the radiation source, the optical length of the measuring part, the value of the reflected power, namely the level of mechanical action and the formed radius of local bending.

It is possible to determine the dynamic range of the meter, with a minimum backscatter signal. The backscattering will be the reverse optical pulse reflected from the bending zone under mechanical action on the optical fiber:

\[ q > q_m + \alpha_1 \cdot l, \]

where \( q \) – is the reflection loss of one optical pulse;
\( q_m \) – losses per reflection of one optical pulse at the output end of a fiber optic conductor;
\( l \) – is the length of the fiber optic meter.

The dynamic range \( W \) can be calculated by the formula:

\[ W = W_0 - 2n \cdot l \cdot \alpha_1 - n q, \text{ dB}, \]

where \( W_0 \) – is the energy reserve of the sensor.
\( R_i / P_{\text{range}}; \)
\( P_{\text{range}} \) – sensitivity digital image sensors, dynamic range;
\( n \) – number of optical connectors in the meter circuit;
\( \alpha_{oc} \) – optical losses introduced by the meter;
\( L \) – is the length of the fiber optic meter;
\( \alpha_1 \) – value of linear attenuation of the pulse in the fiber-optic meter;
\( q \) – reflection loss per optical connection.

4. Discussion and conclusion

Under mechanical action on the optical fiber there are micro and macro bends, leading to additional losses of the optical signal in the fiber. These losses can be measured and pressure values can be set on the optical fiber, and the displacement value can also be determined. An important advantage of this measurement system is its complete spark and fire safety. The energy passivity of the sensors is allowed to exclude power sources that are directly in the area of coal mining. Information-measuring systems of fiber-optic sensors are able to monitor mining operations around the clock.

One of our experiments was the appearance of additional losses due to mechanical action on the optical fiber. When exposed to the fiber optic meter changes the output form of the light spot.

Measurement of rock pressure and rock displacements are two important parameters that can be used to quantify the effectiveness of support for the roof of mining in a given state of geotechnology.

The use of optical fiber standard ITU-T G. 652.D for the control of the coal mine rock mass is very promising since the fiber-optic sensors developed on its basis have a sufficiently high accuracy, speed of measurement and have a good linearity of characteristics. It is not desirable to use fiber with Ultra series as it has a lower sensitivity to bending. Taking into account the above mentioned advantages of FOS our work is aimed at the creation of high-performance IMS based on fiber-optic sensors with improved metrological and operational characteristics for subsequent implementation at various enterprises of Kazakhstan.
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