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# STUDYING ADDITIONAL LOSSES OF STANDARD G.652 OPTICAL FIBER WITH PROTECTIVE CLADDING DURING MULTIPLE BENDING TO DEVELOP WEIGHT CONTROL SENSOR

**[1]ALIYA ALKINA, [2]ALI MEKHTIYEV, [1]YELENA NESHINA, [2]TANSAULE SERIKOV, [1]PERIZAT MADI, [3]KANIBEK SANSYZBAY, [4]ALEXEY YURCHENKO**

[1] Karaganda Technical University, Karaganda, Kazakhstan
[2] Kazakh Agrotechnical University named after S. Seifullin, Nur-Sultan, Kazakhstan
[3] Academy of Logistics and Transport, Almaty, Kazakhstan
[4] Tomsk Polytechnic University, Tomsk, Russian Federation
E-mail: [1]alika_1308@mail.ru, [2]barton.kz@mail.ru, [1]1_neg@mail.ru, [2]tansaule_s@mail.ru, [1]peri@mail.ru, [3]kanibek@list.ru, [4]niipp@inbox.ru

**ABSTRACT**

The article deals with developing an alternative to fiber-optic data transmission lines. One of the problems of telecommunication systems of the Republic of Kazakhstan operation is considered attenuation of signals in FTT data transmission systems. The main idea of using optical fiber of the G.652-656 standard, which is sufficiently sensitive to bends, has been described. Local enterprises have mastered the production of fiber-optic cables and patch cords based on the G.652 standard. Bending causes a loss of the light wave power, changes the phase of propagation of the mode and leads to signal attenuation, in which case users cannot work normally in the Internet. In this article, various types of microbends have been simulated. Microbending of a small radius optical fiber will damage it. This situation arises when the technology of installing a fiber-optic cable is violated. There have been carried out studies aimed at obtaining new scientific results related to the construction of characteristics of additional losses arising from the bending of an optical fiber depending on the number of angles, their degree and the wavelength of optical radiation. Conclusions have been drawn on the further use for the development of sensors based on the control of additional losses during microbending, as well as the development of systems for protecting information transmitted over fiber-optic lines. The studies are aimed at developing software for the numerical calculation of additional losses with an estimate of the accuracy of constructing an approximation according to the given parameters: the number of bends, the angle and wavelength of optical radiation propagating along the fiber core.

**Keywords:** *Optical Fiber, Signal Attenuation, Microbending, Photoelastic Effect, Light Wave, Mode Propagation Phase, Radius, Methods And Means Of Protection, Additional Losses.*

## 1. INTRODUCTION

The intensive development of fiber-optic technology and equipment has been observed for several decades [1]. The transition to optical fiber made it possible to increase the throughput of telecommunication networks and the efficiency of their work. Optical fiber and equipment are improved annually, and their cost is reduced. At present, no alternative to fiber-optic data transmission lines has been developed yet. One of the problems of telecommunication systems in the Republic of Kazakhstan is signal attenuation in FTT data transmission systems. This is caused by the use of optical fiber (OF) of the G.652-656 standard, which is quite sensitive to bending. Local enterprises have mastered the production of fiber-optic cables and patch cords based on the G.652 standard. Bending causes a loss of the light wave power, changes the phase of the mode propagation and leads to signal attenuation, in which case users cannot work normally in the Internet. The change in the parameters of the light wave occurs due to the appearance of the well-known photoelastic effect when bending the fiber. Bending the optical fiber can be divided into two parts: microbend and macrobend. Microbends are characterized by small local violations of the fiber straightness caused by structural and technological inhomogeneities that can arise in manufacturing the fiber, as well as during the cable laying and manufacturing. Fiber macrobends appear as a result of their twisting along the length of the cable and when wound on a drum. In this article, microbends have been simulated that are represented by the word "bending" for simplicity. The bending of an optical fiber with a small radius leads to its damage. This situation arises when the technology of installing a fiber-optic cable is violated. Bending can also be artificially made with unauthorized access to fiber-optic transmission lines (FOL); this is also an existing problem of information security. The analysis of possible channels of information leakage as a result of unauthorized access (UA) is of paramount importance, it is necessary to improve the methods and means of protecting fiber-optic lines. The purpose of this work is studying the additional losses of a G.652 optical fiber with the protective sheath during multiple bending to develop a weight control sensor. The main tasks of the study are as follows: carrying out theoretical studies, computer simulation of a fiber-optic pressure sensor based on the method of measuring additional losses, carrying out laboratory studies, developing a computer program for numerical simulation of additional losses of the G.652 standard fiber, developing a weight control sensor. There have been carried out studies aimed at obtaining new scientific results related to the construction of the characteristics of additional losses arising from the bending of the G.652 standard optic fiber depending on the number of angles, their degree and wavelength of optical radiation. The results will be used in the future for the development of sensors based on the control of additional losses during microbending, as well as the development of systems for protecting information transmitted over fiber-optic lines. The studies are aimed at developing software for the numerical calculation of additional losses with an estimate of the accuracy of constructing an approximation according to the given parameters: the number of bends, the angle and wavelength of optical radiation propagating along the fiber core. The selected bending radius of the optical fiber is close to the critical one, which makes it possible to form the most extreme operating conditions for indoor fiber-optic cables.

## 2. ANALYSIS OF LITERATURE ON THE TOPIC OF STUDY

Today, quartz optical fibers (OF) are widely used in transmission lines of telecommunication and infocom-munication networks: from transcontinental highways of ultra-long distance transport communication networks of a new generation to extremely short connecting lines of compact intra-facility, airborne and industrial/technological networks for various purposes [2]. The latter networks are characterized by "aggressive" operating conditions, in particular, it is limited installation and assembly space, vibration effects and the "dirty" environment. Therefore, for fiber-optic systems, OF with a strongly increased core diameter of 100 μm and more are most demanded [3]. The use of such OF is characterized by a number of advantages presented in work [4]. At the same time, the transition to gigabit technologies requires the use of coherent radiation sources (see IEEE 20 802.3z...ba standards). An optical signal with a limited number of mode components leads to the appearance of new additional negative factors of optical signal distortion [5]. For low-mode optical fibers with an increased core diameter, linear distortions are of primary importance. They are associated with differential mode delay and chromatic mode dispersion. All this makes the transition to low-mode fiber-optic transmission lines based on new low-mode optical fiber one of the most promising fields for implementing perfect communication networks of a new generation [6].

In addition to high metrological characteristics, sensors of a new generation have high reliability, durability, stability and can be compatible with microelectronic information processing devices [7]. In the present day world, among a lot of existing and successfully applied in practice technologies of monitoring and measuring physical parameters, sensors based on optical fiber are considered the most promising [8]. Fiber optic sensors have many advantages over their electrical analogs [9]. These advantages make them attractive for use in all major industries [10]. There have also been considered modern fiber-optic sensors and measuring systems for monitoring objects in harsh operating conditions in various fields [11]. The paper discusses the experience of producing and implementing solutions based on fiber-optic sensors [12]. Modern sensors meet these requirements.

The analysis of work [13] shows that the idea of using optical fiber of the ITU-T G.652.D standard for developing a monitoring system is relevant. In study [14] the object of scientific research is also a quartz optical fiber of the G.652 standard used for the production of fiber-optic cables. Since single-mode fiberglass is difficult to install for very short range networks, this raises the problem of the "last hundred meters" for fiber infrastructure. In work [15], plastic optical fibers are studied, especially with regard to the use of "photonic polymer". Plastic optical fiber has a relatively large core diameter and is flexible enough to be routed for network infrastructure in the last hundred meters. However, plastic optical fiber has two important disadvantages: it has significantly lower bandwidth than single-mode fiberglass and its attenuation is much higher.

In work [16], a system based on fiber bending loss and optical reflectometry in the time domain for monitoring is proposed. The sensor performance is evaluated by the number of fiber loops involved, pump wavelength, and time pulse width. For fiber optic sensors, a simple bending loss formula is achieved. This simple formula takes into account different bend radii, number of turns, additional bend angles and wavelengths, and is in good agreement with theoretical and experimental data. Paper [17] proposes a simplified formula for the sensitivity of the bending loss of a fiber optic fiber. A specific sensitivity formula has the advantage of showing the parameters of fiber optic bend sensor systems. The authors in [18] propose and demonstrate a compact and simple vector bending sensor capable of distinguishing any direction and amplitude with high accuracy. The reflectance spectrum of such a structure is shifted and compressed in a certain way depending on the direction in which the fiber is bent. By simultaneously controlling the wavelength shift and light power changes, the amplitude and direction of the fiber bend can be accurately measured in any degree.

Paper [19] proposes a simple optical fiber displacement sensor with macrobending loss with a large range of motion. As the displacement changes, the light intensity decreases. The sensor is characterized by a large measuring range, simple design, high flexibility and low economic cost, which indicates a promising application in the field of monitoring. A similar development based on macrobending losses is presented in work [20]. The characteristics show that the sensor can be used to monitor movements in large-scale civil structures and has a promising future. In work [21], a displacement transducer is proposed based on the linkage of the bending leakage loss of a fiber, where a twisted structure of two fibers is adopted to compensate for the dissipated loss caused by bending. Here the fiber is stretched, the bend radius becomes shorter. The loss of diffused bending occurs because the lighting fiber has been coupled to the receiving fiber. The sensor has a range of about 150 mm and is used for static, dynamic and planar applications.

This article is a continuation of studies carried out earlier that are related to establishing the parameters of additional losses and developing OF based sensors [13, 14]. The studies are related to the development of an automated method of calculating losses in an optical fiber under mechanical action. [22, 24].

## 3. MATERIALS AND RESEARCH METHODS

The literature review has shown that the most important thing is to reveal the effect of the OF bending on the occurrence of additional losses of the optical power of the radiation (mode) during information transmission. The main selected method is empirical, with the help of which data from practical experiments were collected, and subsequently processed using a computer program. A full-scale model has been developed for carrying out experi-ments on OF bending in laboratory conditions. The obtained data were entered into the program for constructing an automatic approximation of the optical power loss graph for various bending parameters and wavelengths. For re-search, a laboratory bench was specially designed, which allows simulating the real bending of the optical fiber and fixing the optical insertion loss at the exit from it. The value of the loss depends on several factors, and one of them is the value of the bend radius: the smaller it is, the higher the loss. With the critical bending radius, the OF collapses since cracks appear and grow in it. The critical radius is very small (only a few millimeters) for high numerical aperture fibers, while the allowable bend radius is much larger (often tens of centimeters) for single-mode fibers with a large transverse mode area. There are OF standards that are less sensitive to bending, for example, G.657. As it has been mentioned earlier, in the future, the results obtained will be used in other fields of science and technology, for example, to develop fiber-optic sensors and information security systems. The study has been carried out using two methods of measuring additional losses during bending formation.

The first method is based on changing the properties of light when a mode passes through an optical fiber, the effect of light transmission. The experiments have been carried out with optical patch cords 15, 20 and 30 meters long, at the ends of which there are optical connectors of the FS type. The patch cords are made of a single-mode optical fiber of the G.652 125/9 µm (Corning)

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standard with a protective vinyl cladding with the diameter of 248 µm covered with a 0.9 mm thick plastic. The module is placed in a buffer shell with the diameter of 2.8 mm (PVC, Polyvinyl chloride). There is also a Kevlar thread strength element to provide mechanical tensile strength. A standard set of devices has been selected; it consists of an optical radiation source VIAVI (JDSU) SmartPocket OLS-34/35/36 (USA) and an optical power meter VIAVI (JDSU) SmartPocket OLP-38 (USA), the absolute measurement error of which is ±0.2 dB (±5%), the wavelength range from 780 to 1650 nm. Harmonic distortion is ±0.06 dB (from –32 to +20 dBm). The devices used are shown in Figure 1. The wavelengths of the optical radiation source are 1310, 1550, 1625 nm.


*Figure 1: Optical radiation source and optical power meter. The laboratory bench is a base made of 12 mm thick plywood, into which self-tapping screws are screwed. The stand allows simulating any bending angles and their number for patch cords from 20 to 50 meters long*

It is not possible to use patch cords with the length less than 20 meters since this length is not enough for winding and simulating bends. Figure 2 shows the process of winding an optical fiber on a frame to simulate bend-ing angles.

The second method is based on the use of backscattering. It has been implemented using an optical time domain reflectometer (OTDR) manufactured by the YOKOGAWA AQ1200E (Japan). A compensation coil with the length of L=2.8 km has been used. The appearance of the YOKOGAWA AQ1200E OTDR is shown in Figure 3. It has a fairly high accuracy of measuring losses of ±0.05 dB. The dead zone when measuring attenuation of the optical wave is 4 m, when measuring the position of the inhomogeneity it is 0.8 m. The working wavelengths are 1310±25, 1550±25, 1625±10 nm. The measured length ranges from 0 to 512 km, the dynamic range is 32 dB.

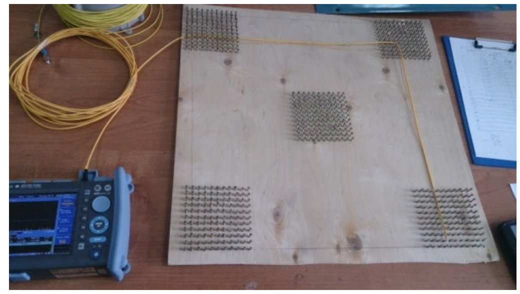

*Figure 2: Laboratory bench*

The limits of the permissible absolute error in measuring attenuation can be determined by the formula:

$$\Delta A = \pm 0.05 \cdot A,$$

where A is the measured attenuation, dB.

The limits of the permissible absolute error when measuring the length are determined by the expression:

$$\Delta L = \pm(1 + 2 \cdot 10 - 5L + \delta),$$

where L is the measured length, m; δ is discreteness of reading in the measured range of lengths, m.

An optical reflectometer of the OTDR type performs averaging of additional losses over a set period of time and ultimately produces an OTDR trace. Inserted additional losses are formed by various connection devices, welding and bending points. The measurement data are presented in the form of numerical values of instantaneous readings and averaged values, as well as a reflexogram of a fiber-optic line section.


*Figure 3: YOKOGAWA AQ1200E optical reflectometer*

The reflectometer calculates the OF length by the expression:

$$l = K_{отр} \frac{\Delta t}{2} * \frac{c_0}{\eta_д},$$

where: l is the OF length, km; Δt is the time difference between the peaks of the initial and the final pulses, s; $\eta_д$ is the actual indicator of the core glass refraction; $K_{отр}$ if the reflection coefficient; $c_0$ is the light speed in vacuum, 300 000 km/s. [22].

Figure 4 shows a schematic diagram of the experiments. The first method is based on changing the properties of light when a mode passes through an optical fiber, the effect of light transmission using an optical radiation source and an optical power meter. In the second method, measurements have been carried out using an OTDR optical reflectometer. In both cases, the value of additional losses has been set.

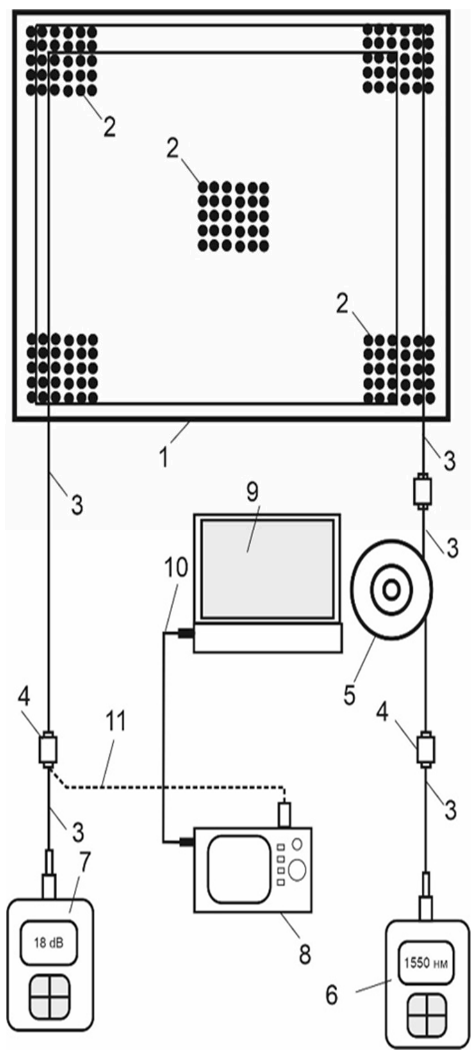


*Figure 4: Measurement scheme: 1- base; 2 - areas of OF winding; 3 - patch cord; 4 - optical connector; 5 - compensation coil; 6 - source of optical radiation; 7 - optical power meter; 8 - optical reflectometer; 9 - laptop; 10 - USB connection cable*

On the base there are 5 winding areas for forming angles of 45, 90 and 135 degrees. The winding areas are square and contain 11 rows of self-tapping screws on each side. To the 6 mm diameter self-tapping screw there is attached a sleeve made of a piece of copper tube with the diameter of 8 mm and the height of 10 mm. The sleeve rotates, which provides tension on the fiber and its safe placement. The experiments involved patch cords with the length of 20 to 50 meters. The winding was carried out with a slight tension to exclude sagging. All the connections were made using FS type optical connectors. Initially, measurements were made using an optical radiation source and an optical power meter. The second step was to take measurements using an OTDR, which was connected to a laptop using a USB connection cable. Since this was the second part of the experiment, the dashed line is shown in the diagram for connecting the optical reflectometer.

To process the experimental data, the known methods are described in work [23]. Justification has been ob-tained for selecting the number of repetitions in order to ensure reliability of the experimental studies results. The number of repetitions was determined by calculating the Квар coefficient and the required degree of accuracy [23]. Subsequently, the data were processed using the Wolframalpha program (available in the public domain), which is an interactive system for processing experimental results and is focused on working with data arrays. After calculating the coefficient of variation and ensuring reliability of 0.95, according to the recommendations of the source [23], the required number of experiments was established. After the Weibull distribution curve was constructed, 30 measurements of additional losses arising in the OF during its bending were randomly selected. The confidence probability P=0.95, the quantile of the Student distribution t=2.0095 for a given confidence probability with the number of degrees of freedom n $k = n - k$ (n, k are the number of suspicious observation results). The relative measurement error was δ=3.5%.

## 4. RESULTS

### 4.1 Results of theoretical studies

An important point is establishing the minimum value of the bending radius, after overcoming which the OF can collapse. The losses are due to the escape of a part of radiation or guided modes outside the core and clad-ding. Losses increase and can become unacceptably large when

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the radius of curvature of the bending decreases to the critical value. The critical bending radius of the fiber is approximately calculated by the formula depending on the wavelength and type of fiber:

$$R_{\text{кр}} \approx \frac{3n_1^2\lambda}{4\pi(n_1^2-n_2^2)^{3/2}}, \text{ mm.} \quad (1)$$

When the fiber is bent at the border of the core and the cladding, the angle of incidence of an electromag-netic wave in the optical range will change, which can lead to a partial loss of radiation power at the output from the optical fiber (Figure 5).

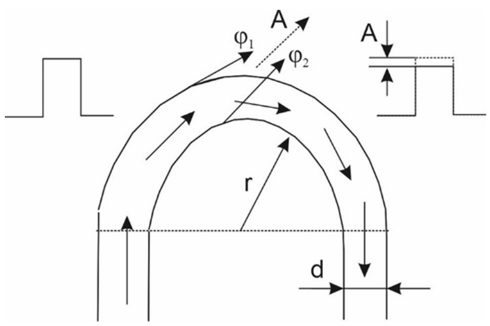


*Figure 5: Escape of a part of radiation outside the core and cladding with OF bending of the r radius with the core diameter d*

The escape of a part of the light wave outside the core and cladding during bending with the OF permissi-ble radius r with the core diameter d, occurs due to changing φ1, the angle of incidence and φ2, the angle of refrac-tion. The additional loss is indicated by the letter A and is shown in the light wave (mode) pulse diagram. It can be seen that a part of the energy of the light wave (mode) is lost, and the pulse amplitude decreases. When overcoming the critical value of the minimum permissible bending radius, the losses will be several times greater. Accordingly, the losses are affected by the number of bending and its radius.

The bend radius r at which radiation will be observed at the bending point of a fiber with the core diameter d, which is associated with the destruction of total internal reflection [22]:

$$r \geq d\frac{n_2}{n_1-n_2}, \quad (2)$$

where: $n_1$, $n_2$ are the indices of the light conductor core and cladding refraction.

Thus, the bending of the fiber leads to violation of the law of total internal reflection, which in turn leads to the lightening of the optical flux outside the OF redistribution.

The OF is able to withstand bending at the angle of ±90° with the radius of no more than 20 times the outer diameter at the normal ambient temperature and at the ambient temperature not lower than -10 °C. On the stand, the minimum bending radius of the optical fiber is within the permissible range and amounted to 4 mm with its diameter of 125 microns, the critical bending radius is about 2.5 mm. The selected optical fiber bending radius is close to the critical one, which makes it possible to form the most extreme operating conditions for indoor fiber-optic cables.

Theoretical studies have shown that depending on the magnitude of the mechanical effect on the OF, there occurs a microbend. This leads to the appearance of additional or so-called introduced losses, while the intensity I of the light wave incident on the surface of the television matrix decreases, and the refractive indices Δn in the optical fiber also change. The refractive index also changes with temperature.

$$\frac{\Delta I}{I} = \frac{1}{I\left(\frac{dI}{qT}\right)k\Delta T} + \frac{\delta I}{I}, \quad (3)$$

where: I is the radiation intensity at the exit from the optic fiber; Δl is the intensity change; $\left(\frac{dI}{qT}\right)k$ is a private derivative of the intensity temperature dependence; δl is the intensity index change due to photoelasticity.

The core refraction index dependence on temperature and deformations can be expressed by the formula:

$$\frac{\Delta n}{n} = \frac{1}{n}\left(\frac{dn}{dT}\right)p\Delta T + \frac{\delta n}{n}, \quad (4)$$

where: n is the OF core refraction index; Δn is the refraction index change; $\left(\frac{dn}{dT}\right)p$ is a private temperature derivative characterizing the quartz glass density changing; δn is the refraction index change due to photoelasticity [14].

When bending, the refractive indices change, which leads to changing the phase of the light wave propagation along the OF core.

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In the mathematical modeling of additional power losses due to attenuation during bending of the optical fiber, an expression has been used that makes it possible to establish the numerical value of attenuation α. The formula is suitable for measuring at the distance of 1 km, which corresponds to the directions of research, since the work consideres internal cables with a vinyl cladding and reinforced with a power element made of Kevlar thread. The expression allows obtaining the ratio of attenuation of the optical signal (mode) depending on the length dB/km and is determined by formula 4:

$$a = \frac{10}{L}\lg\{\frac{P(l_1)}{P(l_2)}\}, \qquad (4)$$

where $P(l_1)$ and $P(l_2)$ is optical power measured in the OF at the points $l_1$ and $l_2$ separated by the $L$ distance.

The attenuation parameter of the optical signal (mode) will exponentially increase with increasing the optical fiber length, while limiting the data transmission range. With increase attenuation of the optical signal (mode) by 3 dB, the power of the proposed signal will decrease by 50 %. The presented results of theoretical studies have been used to study the development of a weight control sensor.

**Computer simulation of the optic-fiber pressure sensor based on measuring additional losses**

The computer simulation method made it possible to visualize the OF bending process. In the course of modeling the bending of the OF was simulated when two metal rods were pressed on it, while the OF was located on two soft bases or, one might say, dampers. The scheme of the experiment and visualization of mechanical stresses are presented in Figure 6 and carried out as follows. With the help of the ANSYS STATIC STRUCTURAL tools, there was made an OF with the thickness of 125 μm, position 1. The OF is pressed by means of two metal rods with the diameter 1 mm, position 2. There was simulated a soft OF, the properties of which corresponded to synthetic rubber, position 3.

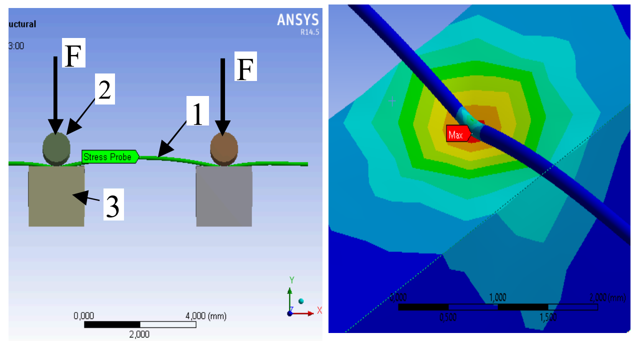


*Figure 6: The experiment carrying out scheme and visualization of mechanical stress: 1 – optic fiber, 2 – steel rods with the diameter of 1 mm, 3 – elastic rubber pad*

Figure 7 shows the simulation results obtained using the ANSYS STATIC STRUCTURAL program. The pressure was varied from 1 to 10 MPa, with a step of 1 MPa, the time of one step is equal to 1 second. Steel rods are spaced 4 mm apart. Within 10 seconds, the OF flexed by 0.207 mm. The dependence of mechanical stresses and deformations on the applied pressure is linear, which was already demonstrated earlier in article [24], which presents the results of studying the OF stretching process.

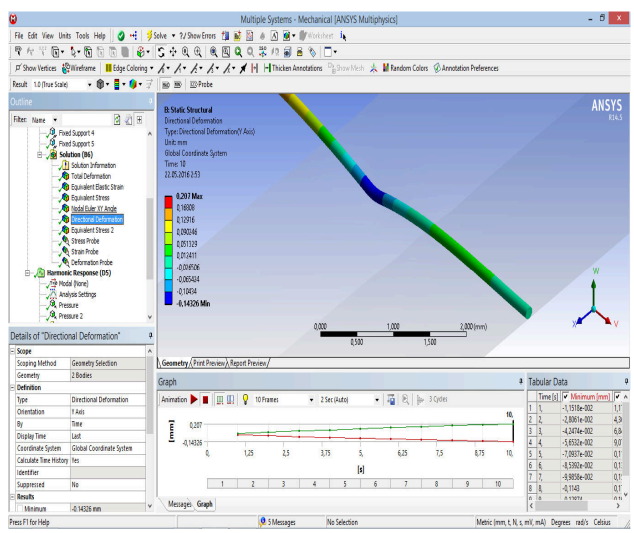


*Figure 7: Simulation results*

There has been obtained visualization that has a different color gamut showing a picture of the propagation of mechanical stresses and deformations.

Using the capabilities of the ANSYS STATIC STRUCTURAL program, it is possible to calculate with a sufficiently high accuracy the mechanical stresses and deformation of the OF under pressure on it at the points marked by the F arrow. Figure 8 shows a graph of the OF deformation changing dependence on changing the pres-sure on it over the period of time from 1 to 10 seconds.

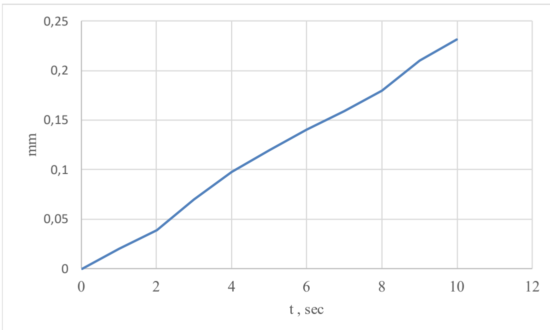


*Figure 8: Equivalent elastic deformation graph*

The program can independently optimize the shape and size of the finite element when breaking the model, which affects the accuracy of calculating mechanical stresses. In accordance with the conditions of the experiment, the elements of the model have been assigned the necessary physical parameters of the materials used. The simula-tion results are used to study the development of a weight control sensor. Accordingly, the OF can be used to develop sensors for pressure, weight, mechanical stresses and deformations with a sufficiently high linear characteristic.

**Results of the laboratory studying an optic-fiber conductor of the G.652 type**

In the process of empirical studies, new results have been obtained. They are presented by graphs of the additional losses growth dependence on the number of bends. For all the experiments, boundary conditions have been set: the number of bends should be in the range of 1-7. The experiments have been carried out in the laboratory at the constant temperature of 22 ± 1 °C. The following devices have been used in the experiments: a YOKOGAWA AQ1200E OTDR optical reflectometer (Japan), a VIAVI (JDSU) SmartPocket optical source (USA), and a VIAVI (JDSU) SmartPocket optical power meter (USA). With the help of the laboratory bench, the imitation of the OF bends at the angles of 45, 90 and 135 degrees has been performed. The bending radius close to the critical one, has been taken within 4 mm for all the experiments. The graph (Figure 9) shows the dependence of the additional losses growth with increasing the number of bends of the optical fiber for three wavelengths of optical radiation: 1310, 1550, 1625 nm. The number of bending angles varied from 1 to 7, the angle has always remained the same and has been 45 degrees.

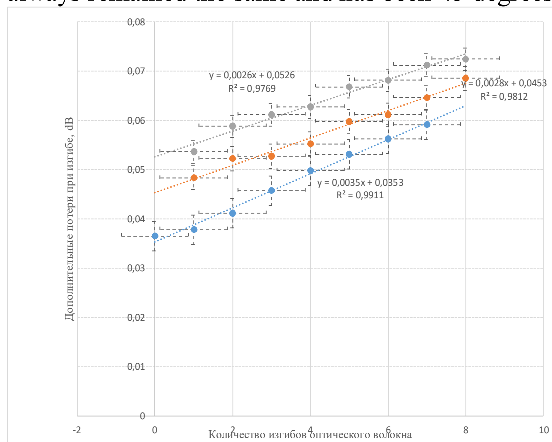


*Figure 9: The graph of the additional losses growth with increasing the number of the OF bends for three wavelengths: 1310, 1550, 1625 nm with the bending angle of 45$^0$*

The graph (Figure 10) shows the dependence of the additional losses growth with increasing the number of bends of the optical fiber for three wavelengths of optical radiation: 1310, 1550, 1625 nm. The number of bending angles varied from 1 to 7, the angle has always remained the same and has been 90 degrees [25].

The graph (Figure 11) shows the dependence of the additional losses growth with increasing the number of bends of the optical fiber for three wavelengths of optical radiation: 1310, 1550, 1625 nm. The number of bending angles varied from 1 to 7, the angle has always remained the same and has been 135 degrees.

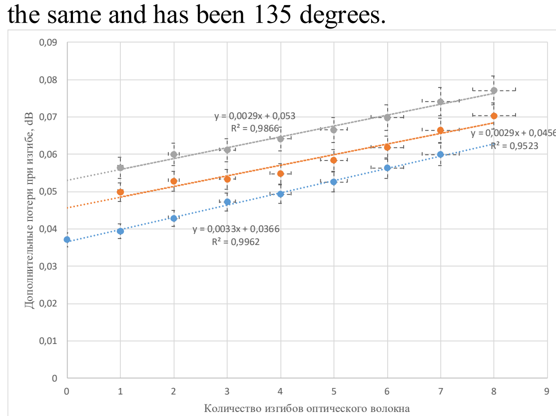


*Figure 10: The graph of the additional losses growth with increasing the number of the OF bends for three wavelengths: 1310, 1550, 1625 nm with the bending angle of 90$^0$*

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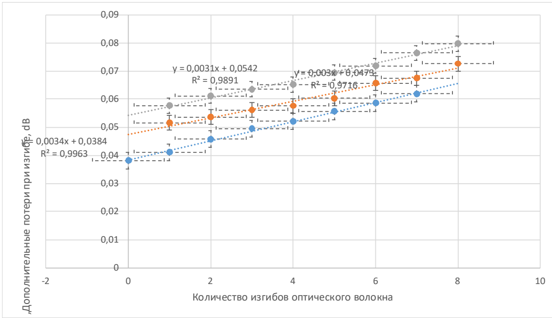


*Figure 11: The graph of the additional losses growth with increasing the number of the OF bends for three wavelengths: 1310, 1550, 1625 nm with the bending angle of 135$^0$*

The optical power losses can reach the maximum of 0.02 dB or more, and they are different at different wavelengths. The longer the wavelength in the range from 950 to 1600 nm, the greater the bending loss of the opti-cal fiber. Based on the data obtained, a computer program has been developed to simulate additional optical fiber losses of the G.652 standard.

## 4.2 The software development results

A computer program for the numerical simulation of additional optical fiber losses of the G.652 standard makes it possible to estimate the additional losses of optical radiation power at multiple bends with the radius close to the critical one. The program is freely available on the site and it can be used by everyone without restriction with the link to the authors of this program [25]. If needed, the number of bends can be increased, but in this version of the program there are limitations: 7 bends are possible for one angle value, so, the maximum number of possible bends is 21. The program is freely available, and any researcher can expand its capabilities.

The program uses the data obtained as a result of empirical research, allows performing linear automatic approximation, builds a trend line and carries out the regression analysis of the results. The program window is shown in Figure 12, an example of a numerical simulation of additional losses causing attenuation of an optical signal at the wavelength of 1310 nm is shown, 3 bends are simulated.

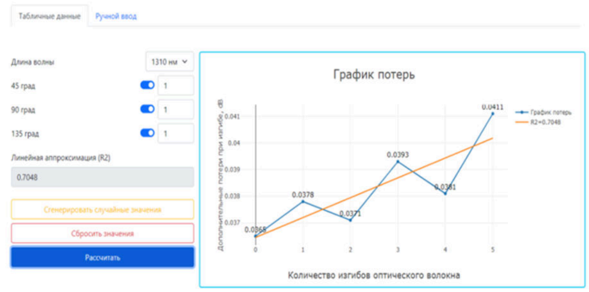


*Figure 12: The Tabular data window*

The program takes into account the following factors in its calculations: the number of fiber bends from 1 to 7; the value of the bending angle of 45, 90 and 135 degrees; the wavelength of optical radiation of 1310, 1550, 1625 nm. The bending radius does not change and always remains close to the critical one within 4 mm. The tem-perature change during numerical simulation is not taken into account, by default it is const = 22 °C.

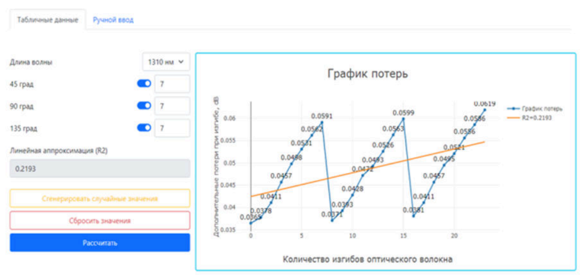


*Figure 13: The calculation of the maximum number of bends*

The program has two windows for entering the calculation data. The first Tabular data window contains numerical simulations based on empirical research data. In the second window "Manual Input" numerical simulation is performed using any data. A linear approximation and a trend line are constructed, as well as the numerical values of the regression R. Below in Figure 14, the window "Manual input" is presented.

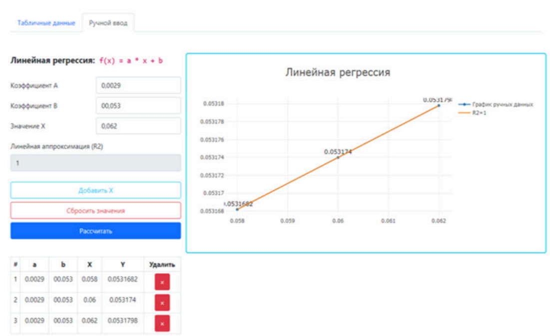


*Figure 14: The Manual input window*

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With numerical simulating additional losses that cause attenuation of the optical signal at the wavelengths of 1310, 1550, 1625 nm, a graph with linear approximation is built using the "Manual Input" tab. In numerical modeling, it is necessary to set the coefficient A that denotes the slope of the line, and the coefficient B denotes its shift, the value of X is an independent variable. Linear approximation (R2) is used to determine the coefficients A and B of linear regression so that all the experimental points lie closer to the straight line. There can also be added multiple values of the X variable. The program can automatically generate the number of bends in a random order. There are buttons for resetting the calculation results and performing the calculation.

**Using the G.652 standard optical fiber additional loss control method to develop a weight control sensor**

The physical principle of operation of a laboratory sample of a fiber-optic weight sensor is based on using the method of measuring additional losses arising in the optical fiber during its bending. The measurement scheme is shown in Figure 15. The sensor consists of a SmartPocket OLS-34/35/36 optical radiation source, a SmartPocket OLP-38 optical wattmeter. A universal UPP 2.5 mm adapter and SC and FC optical connectors are used to connect to the devices. The arrows show the direction of propagation of the light wave from the source to the meter, between which there is the G.652 standard OF.

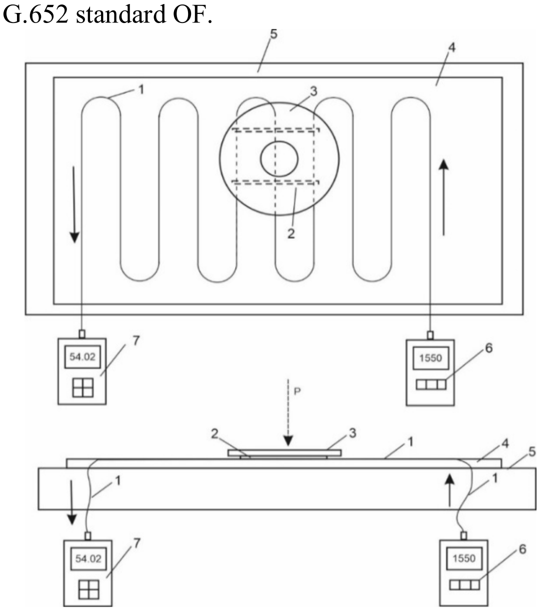


*Figure 15: Measurement scheme: 1 - optical fiber, 2 - metal rod, 3 - disc, 4 - damper, 5 - table base, 6 - light source, 7 - optical power meter*

A light wave with the length of 1331 or 1550 nm is transmitted through single-mode OF 1 in the direction indicated by the arrows. The OF is located on damper 4 and lies on solid surface 5, which does not deform when the load acts on it. Base 5 is the table surface. The direction of load pressure is indicated by the arrow. The OF is affected by two metal rods with the diameter of 1 mm. In the experiments, there has been used the G.652 standard OF with the diameter of 125/9 µm. Additional losses increase with increasing pressure on the OF, that is, the more weight is placed on disk 3, the stronger rods 2 push on the OF. This method allows controlling the weight at the distance of up to 100 km. The measuring point can be located at a considerable distance from the measuring unit. For example, there can be controlled the weight of a vehicle passing over a bridge or a certain section of the road. Along the way, there can be measured the speed of movement of the vehicle if the sensors are located at a redistributed distance from each other. There can also be controlled the temperature of the road surface. In this case, the energy consumption for the operation of one remote sensor will be less than 1 W. Figure 16 shows a photo of the laboratory bench.

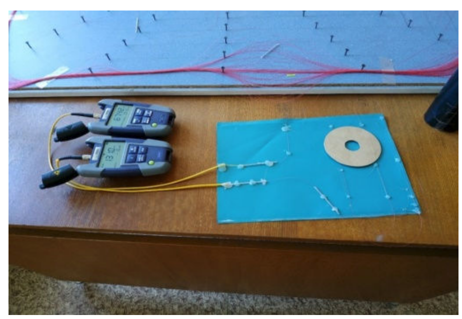

*Figure 16: Laboratory bench*

The initial conditions of the experiment have been as follows: the load weighing 1-10 kg; the room temperature 22 0C; the relative humidity 64 %.

To process the experimental results, the interactive computer program Wolframalpha has been used. As a result of the automated approximation of the obtained experimental data by the Wolframalpha program, the following one-factor mathematical models have been obtained.

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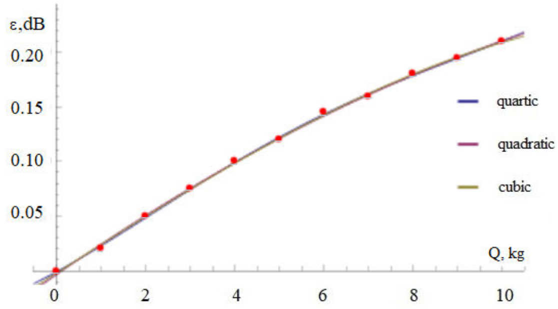


*Figure 17: The OF deformation value ε with step-by-step increasing of pressure on the metal rods*

The deformation values ε dependence is represented by a mathematical model with various types of approx-imation:

$$\varepsilon=0.000016256Q^4 - 0.000358392Q^3+0.00186626Q^2 + 0.0222873Q - 0.00101399 \text{ (quartic)}$$
$$\varepsilon=-0.0000378788Q^3 - 0.000136946Q^2 + 0.0262937Q - 0.00216783 \text{ (cubic)}$$
$$\varepsilon=-0.000705128Q^2 + 0.0284604Q - 0.00353147 \text{ (quadratic)}$$

| Approximati on | AIC | BIC | $R^2$ | Adjusted $R^2$ |
|---|---|---|---|---|
| quartic | –97.4326 | –95.0453 | 0.99948 | 0.999134 |
| cubic | –96.5373 | –94.9457 | 0.999098 | 0.998873 |
| quadratic | –86.288 | –94.4394 | 0.999272 | 0.99896 |

Figure 18 shows the graphs of the percentage of attenuation (loss of optical power) dependence on the applied weight. There is a fairly high linearity of characteristics.

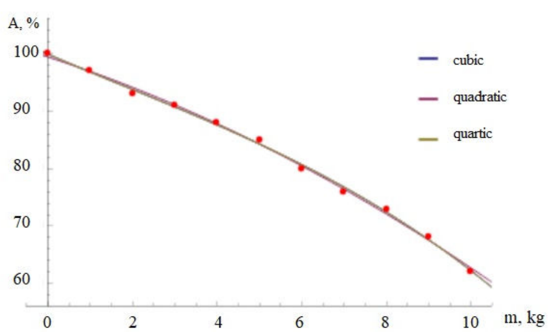


*Figure 18: A graph of the attenuation of a light wave dependence on the applied mass of the load at the wavelength of 1550 nm*

The dependence of the values is better represented by a cubic approximation, at which the Akaike infor-mation criterion is 27.9177, R2 = 0.9979 (the coefficient of determination):

$$A=0.0134033A3+0.0728438A2+3.15734A+99.9231 \text{ (cubic approximation).}$$

## 5. DISCUSSING THE RESULTS AND CONCLUSION

As a result of the study, new scientifically substantiated results were obtained that are valuable for developing an automatic system of controlling additional losses in the optical fiber with bending variations. Based on the method of changing the properties of light when the mode is passing through an optical fiber, the effect of light transmission and control of additional losses with fiber bending can be used to develop fiber-optic weight control sensors.

The result of studying additional losses of the G.652 standard optical fiber with the protective sheath under multiple bending is a specimen of the weight control sensor. Theoretical studies have shown that fiber bending leads to the appearance of additional or so-called insertion losses; at this, the intensity of the light wave incident on the photo-detector decreases, and the refractive indices of the optical fiber also change. The attenuation parameter of the optical signal (mode) will increase exponentially with increasing the OF length, while limiting the range of data transmission. With increasing attenuation of the optical signal (mode) by 3 dB, the power of the proposed signal will decrease by 50 %.

Computer simulation performed with the use of the ANSYS STATIC STRUCTURAL program made it possible to establish a linear dependence of mechanical stresses and deformations on the applied pressure.

Laboratory studies were carried out using a laboratory bench that allows simulating fiber bends at the angles of 45, 90 and 135 degrees. The data obtained confirm that with increasing the wavelength in the range from 1310 to 1625 nm, additional bending losses of the optical fiber increase. Based on the obtained data, a computer program for modeling additional losses of the optical fiber of the G.652 standard, which is in the public domain, has been developed. In its calculations the program takes into account the following factors: the number of fiber bends from 1 to 7; the value of the bending angle of 45, 90 and 135 degrees; the wavelength of optical radiation of 1310, 1550, 1625 nm. The program allows calculating additional losses in the fiber optic cable of the internal laying with G.652 standard optical fiber with the number of bends up to 21, automatic approximating the values of the additional losses that occur in the optical fiber with variations of bend angles and their number. The results of the studies were used to develop a laboratory specimen of a fiber-optic weight control sensor that operates based on the method of controlling additional losses.

In the future, the results of the work can be used to develop methods and means of the security of data transmission over fiber optic lines, since in case of unauthorized access, attackers use devices that develop a bend, which causes slight increasing the value of additional losses and signal attenuation, since these two parameters are interconnected. In the future, studies will be continued in the field of developing methods of controlling the weight of vehicles passing over a bridge or a certain section of the road.

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