Development of a model fiber-optic sensor of the external action on the basis of diffraction gratings with variable parameters of the system

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Abstract. Physical and mathematical model of the control system parameters of the optical signal using the sensor of the external action on the basis of a diffraction grating with variable characteristics (the lattice period; the width of the transparent strip (zone); width of the absorbing strip (zone)) are developing. A mathematical model of the diffraction grating is constructed on the basis of equations to calculate the resulting intensity and amplitude of the interference light passing through the grating. For the model of a lattice with a round hole, equations containing special functions of the Bessel function type, calculated numerically by calculating convergent infinite power series and integrals which are not calculated analytically, are proposed. The degree of accuracy of the developed model is determined by the severity of the underlying fundamental equations of theoretical and mathematical physics.

1. Introduction
Detailed analysis of modern developments in the field of practical application of fiber-optic sensors (FOS) from leading scientists in Russia and Western Europe showed that the main directions of technological implementation of the results of theoretical and experimental studies to improve the physical characteristics (range of wavelengths and intensities of optical signals; miniaturization of recording devices, etc.) FOS refers to diagnostic, control and measuring equipment (medical physics, biotechnology, military-defense equipment, mining and engineering technologies, aviation and transport industry) and technologies of communication systems, radio and telecommunications. Of particular interest for technology are devices based on FOS, working in extreme conditions: strong electric and magnetic fields; intense coherent (laser) radiation; inelastic deformation and mechanical stress; ultra-low and ultra-high temperatures, etc.).

The use of FOS in the mining industry remains unresolved to date. This industry specializes in the extraction of various minerals and is in constant development, as new deposits are opened, which require the use of specialized equipment and innovative technologies. Therefore, all mining enterprises are equipped with high-quality, modern and modernized equipment. However, there are certain problems that hinder its development. To them in the first place is security and performance. Many enterprises of the mining industry have been working for a long time and use outdated facilities, as a
result of which the entire territory, the soil, are exposed to a certain negative impact. Therefore, it is necessary to pay special attention to the equipment of production with special systems and specialized equipment, which will ensure the safety and increase the productivity of work performed at the quarry. Currently, the issues of ensuring the safety of open minerals in terms of the stability of the sides of the quarry and berm, as well as the timely prediction of their sudden collapse remains unresolved.

Monitoring systems of the new generation with high measurement speed are able to function effectively in conditions that are dangerous due to sudden explosion of methane gas, as they do not transmit electrical signals. Safety of mining operations is an important aspect and priority of the complex system of the mine [1, 2].

Currently, in the most technologically advanced countries of the World, fiber-optic transmission systems (FOS) of signals are widespread and implemented at almost all levels of information and communication infrastructure. Compared with existing analogues of communication systems on copper cables, FOS have a number of technical advantages. Wide bandwidth allows you to organize one fiber-optic path with the required number of channels and the possibility of their further expansion. This communication system provides the subscriber, along with telephone communication, any kind of communication services (television, fax, broadband radio, reference services, advertising, local communication, etc.). Additional advantages include a high degree of protection of the VSP system from unwanted external electromagnetic influences (interference), small kilometer attenuation, the possibility of organizing long-range regeneration sites, as well as significant savings in copper and potentially low cost of optical cable, etc.[3, 4].

The important components of modern fiber-optic communication technologies are the means of monitoring and measuring the parameters of optical signals, as well as devices that allow you to adjust the signal intensity and wavelength. Improvement and development of electronic-optical schemes for control-measuring and diagnostic systems of VSP are actual and demanded in practice the research direction.

2. Principle of operation and operation of fiber optic sensors
Fiber optic sensors are divided into two types: the first type of sensors in which during the propagation of light through the optical fiber, the phenomenon under study affects the light; the second type of sensors having an external sensing element in which light is derived from the optical fiber is influenced and re-launched into the fiber for transmission and signal processing. In this paper, sensors with an external sensing element were considered, in which the physical mechanism for converting the optical signal parameters is based on the effect of a diffraction grating. Diffraction grating is an optical device, the principle of which is based on the phenomena of diffraction and interference, which has a periodic structure and is a set of transparent (or translucent) and absorbing bands alternating with the period s (Figure 1). Gratings are used to measure a variety of characteristics, and for all this, both the intensity and the wavelength are used for measurements. The principle of operation of the gratings is based on modulation, which manifests itself as a change in the intensity and wavelength. But before analyzing the properties of optical gratings it is necessary to consider diffraction. The simplest case is diffraction on a single slit, where light passes through a narrow slit and is projected onto the screen.

The key characteristics of the diffraction grating are the grating period s and the transparent fragment of each period a. The total amount of energy passing through the near field is proportional to the $\frac{a}{s}$ ratio.

In virtual laboratory conditions, sensors are usually considered or modeled on the basis of measurement of the intensity of the resulting optical signal, determined depending on the lattice parameters $I(\xi) = I_0 k(\xi)$ where $k(\xi) = \frac{a(\xi)}{s(\xi)}$ - the attenuation coefficient of the total intensity of the interfered waves in the lattice, expressed in terms of the ratio of the lattice width $a(\xi)$ and $s(\xi)$.
period, which are functions on \( \xi = \{\xi, \frac{1}{\xi}\} \) a set of variable system parameters. For such parameters in developing *nonlinear* mathematical models can be attributed to geometrical parameters, optical characteristics of the wave (the wave vector, the valley of the waves) and the temperature \( T \).

![Figure 1. Structure of the diffraction grating.](image)

In the particular case, when \( s(\xi) = \text{const} \) the intensity of the modulated transmitted light is equal to \( I(\xi) = I_0 \frac{a(\xi)}{s} \). This type of modulation can be obtained as a result of the relative motion of two diffraction gratings located in close proximity to one another. In sensors where diffraction gratings are used that are close to each other, there are ultra-sensitive elements. One of them is mobile, and the other is not mobile. The intensity measurement of the two gratings can be seen in (Figure 2). When the gratings are located close to each other, then to the penetrating light they appear as one lattice and the lattice period \( s \) remains constant, and the proportion of the transmission area will vary in the aisles from 0.5 to 0 depending on the position of the movable lattice.

We can immediately conclude that 100% change in intensity will be when the lattice shifted from each other by value \( a(\xi) \). And at the same time, the offset sensitivity and dynamic range are adjustable together. Ultra-high sensitivity is obtained due to the dynamic range [2]. Fiber optic sensors with movable gratings can be used to measure any parameter, the change of which is manifested through the movement and movement of the two gratings.

Diffraction gratings can also be used as wavelength-responsive devices. If the relation is \( k(\xi_1, \xi_2) = \frac{a(\xi_1)}{s(\xi_2)} = \text{const} \), where the lattice period is modulated by some \( \xi_2 \) parameter of interest. For example, at a constant registration angle \( \theta \) a constant input angle and a uniform distribution of energy over wavelengths, the color recorded in the input signal will be directly related to the \( \xi_2 \) parameter. In this case, the lattice is embedded or attached to the substrate selected to measure the deformation caused by the studied parameter. If, for example, a substrate with a large coefficient of thermal expansion is selected then the lattice period will be determined from the \( s = s_0[I + \alpha(T - T_0)] \) expression where the coefficient \( \alpha \) – of thermal expansion of the material; \( s_0 \) – the lattice period at \( T_0 \) temperature.
When illuminating a reflective diffraction grating with periodic reflecting and absorbing bands with broadband light at $\theta_1$, a constant angle, the diffraction of light depends on the grating period $s$ (the distance between the centers of the reflecting bands) and $\theta_2$, the registration angle in accordance with the grating equation

$$s(\sin \theta_0 + \sin \theta_1) = \pm m\lambda,$$  \hspace{1cm} (1)

where the angles are $\theta_1$, $\theta_2$, an angle, measured in the plane of incidence of light normal to the lattice.

The value $m$ is the diffraction order given by an integer. The bars are perpendicular to the plane of incidence. The incident radiation’s input angle with a lattice is 10°, and the output is 40°. Both corners are located on the same side from the center to the grid. Input fiber and output fiber placed at a distance of 3 and 4 cm to each other from the grid. As an optical source there was used a laser. The grating was fixed on the translational displacement table that was used in the experiment to obtain the input position. The curve (Figure 3) was obtained by measuring the spectral intensity distribution at each displacement per millimeter of the table being moved over the entire range of its movements. From all these studies we can finally conclude. This method allows for high-precision measurements of linear displacements using input and output fiber optics.

**Figure 2.** Modulation of the intensity of lattices opposite to each other.

**Figure 3.** The ratio of the measured provision and the actual provision of the grid.
3. Methods of regulating the intensity of the signal using a diffraction grating

Modern methods of experimental and theoretical research in the field of fiber optic technology are based on achievements in the field of optoelectronics, wave technology and nonlinear optics. When performing the schematic diagrams of optoelectronic devices for monitoring and controlling the parameters of various levels of complexity of technological processes, it is important to address the issue of the development of high-speed systems for automated control of the wave characteristics of the light flux (pulse) entering and exiting the fiber channel. The question of the development of universal theoretical methods for the description of nonlinear electrical-optical processes implemented in the working channels of control and measuring fiber-optic devices (sensors, wavelength converters; signal intensity amplifiers; electronic interferometers, etc.) operating in a wide range of optical radiation parameters (intensity, wavelength, etc.) remains open. The question of development of effective methods of computer forecasting of properties of materials for working elements of fiber-optic devices that represents the separate theoretical problem which closely connected with experimental and production tests and based on methods of the theory of a solid state, wave physics and quantum electronics is an actual question.

The amplitude of the total signal from the waves interfered in the lattice, with the total number of strokes in the lattice \( N \), is calculated using the condition of the maximum interference from two waves diffracted on one slit \( \Delta_{1,2} = s \cdot \sin \varphi \), where \( \Delta \) is the path difference and \( \varphi \) is the angle of observation of the interference from two waves, in the form of

$$\Xi = \Xi_1 \sin \left( \frac{N \varphi_{1,2}}{2} \right). \tag{2}$$

Here is \( \varphi_{1,2} = k \cdot \Delta = \frac{2 \pi s \cdot \sin \varphi}{\lambda} \) and accordingly, \( \frac{\varphi_{1,2}}{2} = \pi s\zeta \) is a half of the phase difference of two coherent waves, where \( \zeta = \frac{\sin \varphi}{\lambda} \); \( \Xi_1 = \Xi_0 \sin \left( \frac{\varphi_{1,2}}{2} \right) \) — the total intensity of the wave obtained as a result of interference from two coherent waves in the model of one slit \( \Xi_0 = 2L \); the doubled radius of the circle described around the polygon of characteristic vectors of the phase diagram of the interference pattern.

The value of the intensity of the total light flux obtained as a result of the interference of coherent waves from all \( N \) slits of the lattice, under the angle of observation of \( \varphi \) the interference, is calculated as

$$I = I_1 \frac{\sin^2 \left( \pi s\zeta N \right)}{\sin^2 \left( \pi s\zeta \right)}, \tag{3}$$

where \( I_1 = I_0 \frac{\sin^2 \left( \pi a\zeta \right)}{(\pi a\zeta)^2} \); \( I_0 \) is the intensity of the light flux obtained by the interference of coherent waves, from a single slit, under the angle of observation of the interference \( \varphi = 0 \).

When choosing round holes, as a result of Fraunhofer diffraction on one round hole with diameter \( d \), we have
\[ I = I_1 \frac{J_N(\pi d \varsigma)}{J_1(\pi d \varsigma)}, \quad (4) \]

where \( I_1 = 2I_0 \frac{J_1(\pi d \varsigma)}{\pi d \varsigma}; \ J_1(\pi d \varsigma) \) is the 1st order Bessel function computed from the argument \( \frac{\varphi_{1,2}}{2} = \pi d \varsigma; \ J_N(\pi d \varsigma N) \) is the Nth order Bessel function computed from the argument \( \frac{\varphi_{1,2} N}{2} = \pi d \varsigma N. \)

In the study of Bessel functions we will use a number of well-known expressions. In the case \( z = \pi d \varsigma N < 1 \) it is possible to apply expansions in infinite power series

\[ J_N(z) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k! \Gamma(N+k+1)} \left( \frac{z}{2} \right)^{N+2k}, \quad (5) \]

where the gamma of functions is calculated from equality \( \Gamma(N+k+1) = (N+k)!. \)

Special functions such as Bessel, Hankel, Neumann and hypergeometric functions previously tested in the construction of a physical and mathematical model of nonlinear electrophysical processes occurring in heterogeneous electrical, radioelectronic and optoelectronic systems based on proton semiconductors and dielectrics were used in the development of the theoretical foundations of this technology [7-10].

4. Principles of operation of complex fiber-optic regulatory systems

The principle of operation of the multiplexer and demultiplexer is based on the known phenomena of physical optics: dispersion, diffraction and interference. Their structure can be based on an optical prism, a multilayer dielectric, a diffraction grating, etc.

In multilayer structures, you can select the wave transparency zone and the width of this zone. Structurally, the multiplexer is a multilayer dielectric structure clamped on both sides by two rod lenses. The end surfaces of the lenses are covered with an absorbing dielectric film. The optical axes of the lenses and fibers are shifted relative to each other. In most cases, these devices have the following characteristics: the number of waves 2-6, direct losses 2...5 dB, transient attenuation 20 ...40 dB, the intervals between the wavelengths are 30...100 [5].

The multiplexers based on grating the dependence of the diffraction angle of the beam passing through the diffraction grating of the reflective type on the wavelength is used. Therefore, placing \( S \) in places of formation of light spots corresponding to different wavelengths provides possibility to achieve the separation of light waves along the length. Structurally, these MP are as follows. A reflective diffraction grating is glued to one end of the rod lens. The separation properties of the filter are determined by the selectivity of the diffraction grating along the wavelength and core diameter of the input and output \( S \). The bandwidth is proportional to the diameter of the core, so the input and output optical fibers of larger diameter are used for its expansion. Multiplexers based on the Diffraction grating have the following characteristics: transparency band of about 20 nm, direct loss of no more than 4 dB, transient attenuation up to 40 dB.

5. Conclusion

The following conclusions can be drawn from the work performed. The theoretical and methodological foundations of the nonlinear physical and mathematical model of optical (wave) processes occurring in the diffraction grating (with rectangular holes), which acts as a fiber optic sensor of external action, with variable characteristic parameters of the system are laid. The characteristic parameters of fiber optic sensors are geometric (the width of the transparent band, the
period of the diffraction grating, the angle of incidence of light flux on the grating, etc.) wave (wave vector, wavelength, intensity of light radiation, etc.) and temperature (coefficient of linear expansion of the material, temperature) parameters of the fiber optic system. The proposed technical solutions will find practical application in the development of high-speed high-precision recording devices designed to control, regulate and predict the physical and mechanical characteristics of rock formations, which is important for the modern mining and coal mining industry.

References
[1] Yurchenko A V, Mekhtiyev A D, Bulatbaev F N, Neshina Y G, Alkina A D and Madi P Sh 2019 Investigation of additional losses in optical fibers under mechanical action IOP Conference Series: Materials Science and Engineering 516(1) doi:10.1088/1757-899X/516/1/012004
[2] Yurchenko A V, Mekhtiyev A D, Bulatbaev F N, Neshina Y G, Alkina A D, Alkina A D, Kokkoz M M 2017 The clearance control system of the lever-hinge mechanism of the mine winder braking device using the capacitive sensors Journal of Physics: Conference Series 881(1) 012034
[3] Serikov T G, Yakubova M Z, Mekhtiev A D, Yugay V V, Muratova A K, Razinkin V P, Okhorzina A V, Yurchenko A V 2017 The analysis and modeling of efficiency of the developed telecommunication networks on the basis of IP PBX asterisk now Proceedings - 2016 11th International Forum on Strategic Technology IFOST 2016 7884168 510-515
[4] Yurchenko A, Mekhtiyev A, Neshina Y, Alkina A and Yugai V 2019 Passive Perimeter Security Systems Based On Optical Fibers Of G 652 Standard Proceedings of International Conference on Applied Innovation in IT 7(1) 31-36
[5] Boutiques E I 2003 Optics (BHV-Petersburg)
[6] Korn G and Korn T 1973 Handbook of mathematics (Moscow. Publishing House "Science")
[7] Kalytka V A, Korovkin M V, Mekhtiev A D, Yurchenko A V 2018 Non-linear polarizing effects in dielectrics with hydrogen bonds Russian Physics Journal 61(4) 757-69 DOI: 10.1007/s11182-018-1457-8
[8] Kalytka V A, Korovkin M V 2016 Quantum effects at a proton relaxation at low temperatures Russian Physics Journal 59(7) 994-1001 DOI: 10.1007/s11182-016-0865-x
[9] Kalytka V A, Korovkin M V 2017 Dispersion relations for proton relaxation in solid dielectrics Russian Physics Journal 59(12) 2151-61 DOI: 10.1007/s11182-017-1027-5
[10] Annenkov Yu M, Kalytka V A, Korovkin M V 2015 Quantum effects under migratory polarization in nanometer layers of proton semiconductors and dielectrics at ultralow temperatures Russian Physics Journal 58(1) 35-41. DOI: 10.1007/s11182-015-0459-z