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The Information-Measuring System for Space Technology Monitoring

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Abstract. The purpose of the research was to validate the choice of fiber-optic measuring instruments for space technology. It is shown that the information-measuring system meets the requirements of the system being operated in the special conditions of rocket and space engineering and of the objects of the ground space infrastructure. In addition, the task was to research the fiber-optic information-measuring system to determine the metrological characteristics and further evaluation of the system efficiency. The developed information-measuring system includes a fiber-optic strain and temperature sensors. The sensing tip of the fiber forms fiber Bragg gratings (FBG). The temperature and strain readings are obtained by measuring the shift of the resonance FBG wavelength by the built-in spectrum analyzer. The results of the study showed that the sensitivity of the FBG was 11.2 pm /°C for the positive range (from 25 to 300 ° C) and 9.1 pm /°C - for the negative temperature range (from -80 to 25 ° C). The deformation ratio of FBG in the range up to 1200 µm (0.012 µm) was $K = 0.6 \pm 0.3[1/\mu\varepsilon]$. The comparison of the calculated and experimental data showed minor discrepancy between the predicted and experimental values, which confirms the correctness of the constructive decision and system efficiency of the developed information-measurement system.

Keywords: fiber Bragg grating, information-measuring system for monitoring, measuring cell, sensitivity

Introduction

The definition of the measurements occurring inside the technically difficult objects is of interest for various science fields. Among fiber-optical measuring systems one of the most widespread types are systems on the basis of sensors with Bragg gratings.

Sensors with Bragg gratings, as well as other fiber optic sensors (FOS), have a number of advantages, which favourably distinguish them from the sensors constructed on other physical principles. The main of them are the following: small weight and small dimensions of sensitive elements caused by the small diameter of the very optical waveguide (~100 μm); high reliability and reproducibility of measurements caused by stability of the used registration methods of optical radiation, including application of spectral methods; high fire safety caused by absence in designs of sensitive elements of electric currents and the heated areas and also a possibility of using non-flammable substances; high dielectric durability – tension of electric breakdown of quartz glass is ~10 kV/mm (20 °C) and ~2.5 kV/mm (500 °C); possibility of carrying out the multipoint and distributed measurements, including with using spectral and spatial multiplexing of the sensitive elements located in one or in several optical fibers.

The FOS sensitive element, on the basis of which the developed information and measuring system is built, is a fiber Bragg grating (FBG). It is created on optical fiber and is only several millimeters in length. Such sizes are very close to the sizes of point sensors, however, if the set of sensors with FBG is created on different wavelengths and demodulated by the system with temporary division, the total amount of such sensors on one fiber is limited by the width of a source range and a radiation detector. Up to one hundred sensitive elements with FBG for the creation of the distributed system intended for measurement both deformations and temperatures can be built on one fiber.

In fact, there is no object of control or production, which would not be affected by deformation and temperature loads. In this regard, the developed system is especially important and up-to-date in the field of monitoring of products of space equipment.

The operation principle of the converters with FBG

During the development efforts in Joint Stock Company "Research institute of physical measurements" development of the distributed microoptoelectromechanical measuring and functional modules providing measurement of temperature and deformation of the basic bearing designs of products of the missile and space equipment and objects of ground infrastructure (IFMOT and IFMOD) is conducted.

The design, formation methods, and the basic operation principles of FBG are described in [1-3]. The most important property of FBG is narrow-band reflection of optical radiation, which relative spectral width can make 10^{-6} and less. The radiation extending on optical fiber is possible to present in the form of combinations of its own modes: directed and radiating. If there is no disturbance in optical fiber, the modes extend without interaction with each other.

The structure of FBG is built in such a way to provide necessary resonant interaction between the chosen modes of an optical fiber. Interaction of modes in an optical fiber is usually described by means of the theory of the bound modes [2], where it is supposed that on a certain wavelength only two modes meet a condition of phase synchronism and can transfer effectively each other energy. FBG connect the main mode of an optical fiber with the mode extending in an opposite direction. Two modes interact on a uniform lattice of refractive index, that is on structure, in which the refractive index periodically changes with the constant period of L, if a condition of a phase synchronism is satisfied:

$$\beta_2 - \beta_1 = 2\pi N / \Lambda \tag{1}$$

where b1 and b2 are the propagation constants of the describing modes, N is an integer characterizing an order, where an interaction between modes is performed. Mode propagation constant is expressed by the ratio

$$\beta_i = 2\pi n^i_{eff} \big/ \lambda \tag{2}$$

where n^i_{eff} is an effective refractive index if the i-th mode, l is a wavelength in a vacuum.

Types of intermode interaction for N = 1 are given in Fig. 1. On a vertical axis the effective index of refraction of modes OV, where n_{co}, n_{cl} and next are the indices of a core refraction, cover and external environment respectively is laid. The positive and negative directions of a vertical axis characterize the modes of optical fiber extending in relation to initial main mode of HE11 in the direct and return directions respectively. Dispersion curves for the modes of the core ($n_{ext} < n_{eff} < n_{co}$) and cover

($n_{ext} < n_{eff} < n_{cl}$) are shown. A shaded area corresponds to the radiating modes of OB. 1 and 2 dashed lines are the values $n_{eff}^{co} - \lambda/\Lambda$ for the gratings with a small L_{BG} £ 1 μ and bigger (long-period fiber gratings) L_{LPG} ³ 100 μ periods respectively (n_{eff}^{co} is an effective refractive index of the main mode).

Crossings of curves with dispersive curves of various modes set lengths of waves, on which the condition of phase synchronism is satisfied (1)

$$\lambda_{BG} = 2 n_{eff}^{co} \Lambda_{BG} \tag{3}$$

The properties of this reflection depend on the grating parameters. For a uniform grating of length L reflection coefficient R on the resonant wavelength of l_{BG} is expressed as $R = th^2(k_{BG}L)$, where $k_{BG} = p\mathrm{D}n_{mod}h_{BG}/l_{BG}$ is coupling coefficient. Dn_{mod} is a modulation amplitude in the first order of decomposition of a stroke form into the Fourier series, a part of power of the main mode, which extends on a core of an optical fiber of radius of a. E_{co} is an amplitude of the electric field of the main mode.

Dependence of the Bragg wavelength on temperature differential can be written down as:

$$\Delta\lambda_{\mathbf{BG}} = \lambda_{BG}(\zeta + \alpha)\Delta T \tag{4}$$

where $\alpha = \left(\frac{1}{\Lambda}\right)\left(\frac{\partial \Lambda}{\partial T}\right)$ is a thermal coefficient (0.55·10^{-6} °C^{-1}); $\zeta = \left(\frac{1}{n}\right)\left(\frac{\partial n}{\partial T}\right)$ is a thermooptical coefficient (8.6·10^{-6} °C^{-1}) for a quartz core of the optical fiber with alloying by germanium.

For simultaneous measurement of deformation provided that temperature coefficients for them significantly differ from each other, a system of the equations

$$\begin{pmatrix} d\lambda_{BG}^1/\lambda_{BG}^1 \\ d\lambda_{BG}^2/\lambda_{BG}^2 \end{pmatrix} = \begin{pmatrix} K_\varepsilon^{01} & K_T^{01} \\ K_\varepsilon^{02} & K_T^{02} \end{pmatrix} \begin{pmatrix} d\varepsilon \\ dT \end{pmatrix} = \overline{K} \begin{pmatrix} d\varepsilon \\ dT \end{pmatrix} \tag{5}$$

has a determinant other than zero ($\det(\overline{K}) \neq 0$) and can be solved analytically relative to $d\varepsilon$ and dT:

$$\begin{pmatrix} d\varepsilon \\ dT \end{pmatrix} = \overline{K}^{-1} \begin{pmatrix} d\lambda_{BG}^1/\lambda_{BG}^1 \\ d\,\lambda_{BG}^2/\lambda_{BG}^2 \end{pmatrix} \tag{6}$$

Thus, when using two FBG (for measurement of temperature and deformation) the task is reduced to that the spectral response of gratings is various at change of temperature or at the application of deformation (compression / stretching force), the size of which is required to be measured.

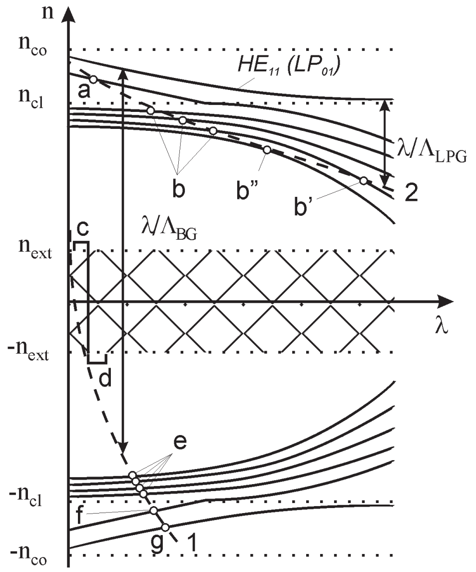


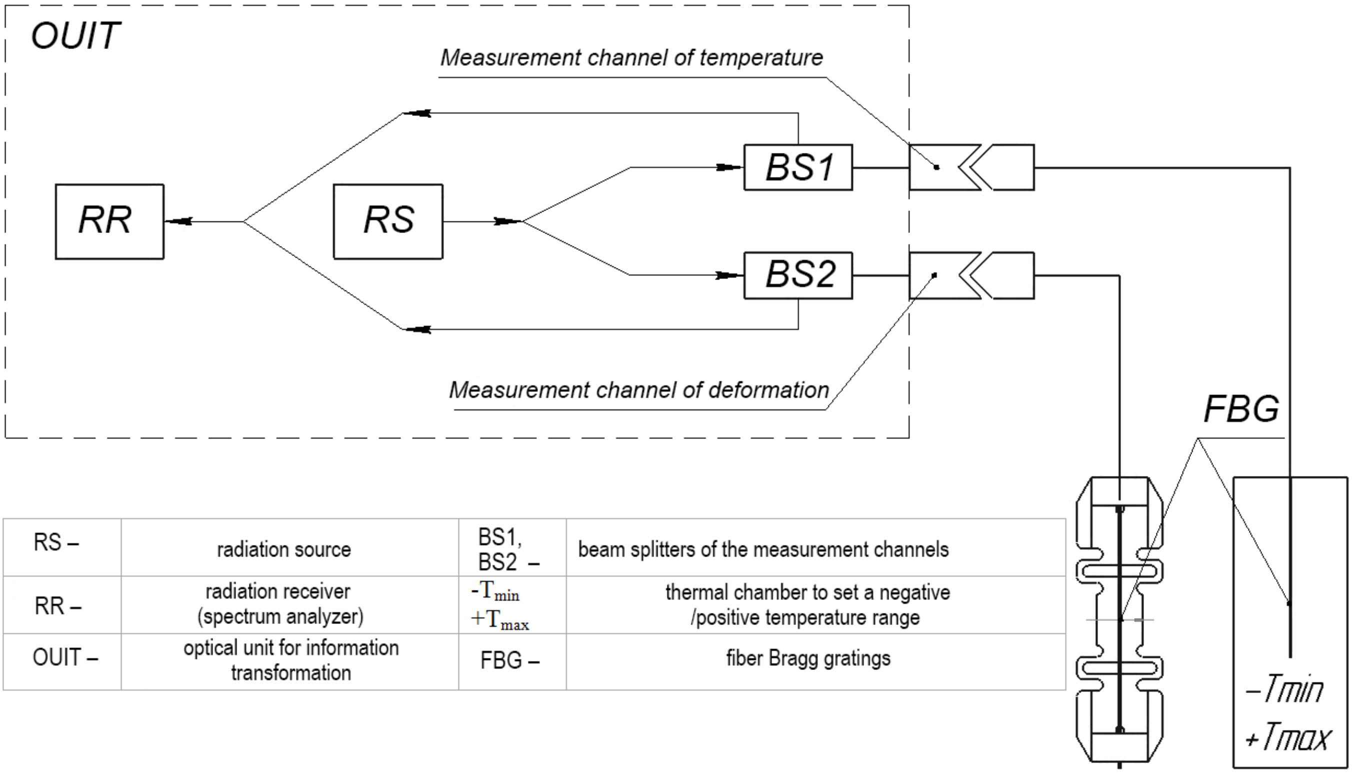
Fig 1. The chart showing the performance of a condition of phase synchronism between the main mode of HE_{11} (LP_{01}) and other modes of optical fiber.

Experimental studies

The block diagram of the monitoring measuring system is given in Fig. 2.

The source of radiation forms a light stream with wavelength in the range of 1550 … 1590 nm, which extends on an optical fiber. A spectrum analyzer is used as a radiation receiver. This analyzer is necessary for display and research of reflection ranges of the Bragg wavelengths. Measurement of reflection ranges was carried out on the Bragg wavelength of 1550±0.5 nm (for measurement of temperature) and 1538±0.5 nm (for deformation measurement) with reflection coefficient of 70% in normal climatic conditions.

Experimental studies on influence of the increased temperature in the range from 25 to 300 °C, the lowered temperature from -80 to +25 °C (Fig. 3 and 4) are conducted. At influence of the increased and lowered temperature, the shift of the Bragg wavelength towards increase and reduction respectively is observed. Load also leads to the shift of the Bragg wavelength of the measuring functional optical module of deformation.



RS –	radiation source	BS1, BS2 –	beam splitters of the measurement channels
RR –	radiation receiver (spectrum analyzer)	$-T_{min}$ $+T_{max}$	thermal chamber to set a negative /positive temperature range
OUIT –	optical unit for information transformation	FBG –	fiber Bragg gratings

Fig. 2. A block diagram of the information and measuring system

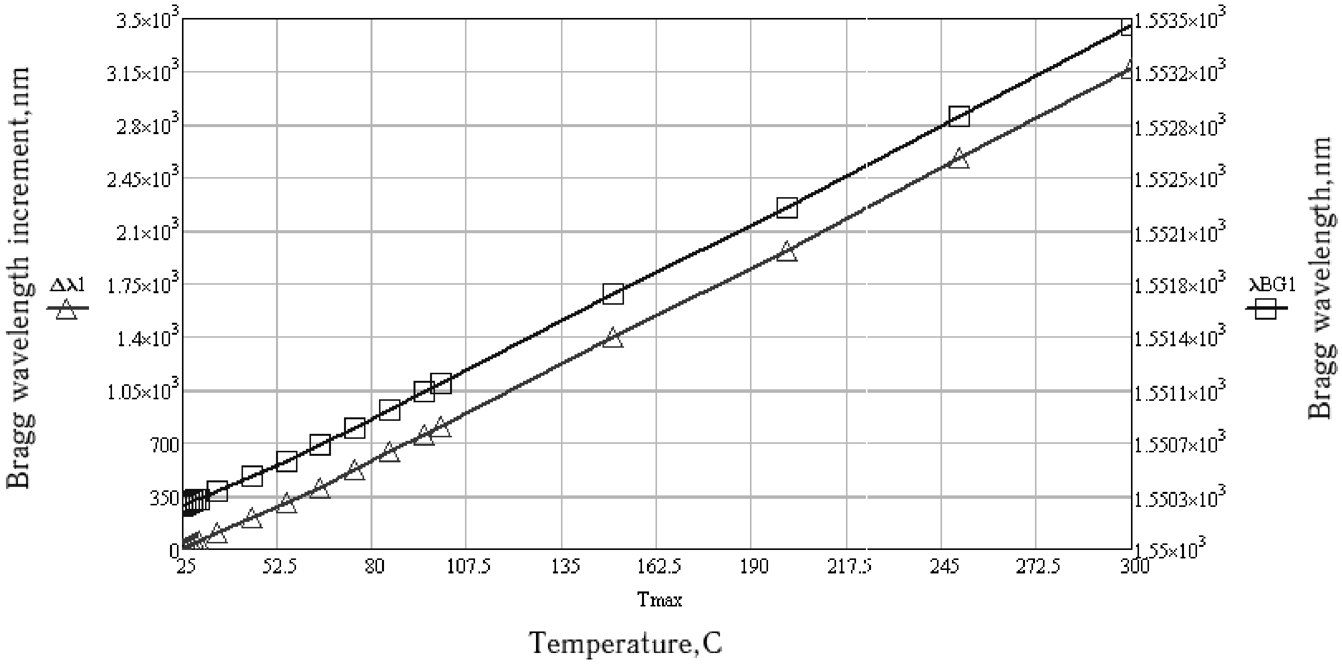


Fig. 3. Functional dependence of shift of the Bragg wavelength $\Delta\lambda_{BG1}$ on temperature in the positive range

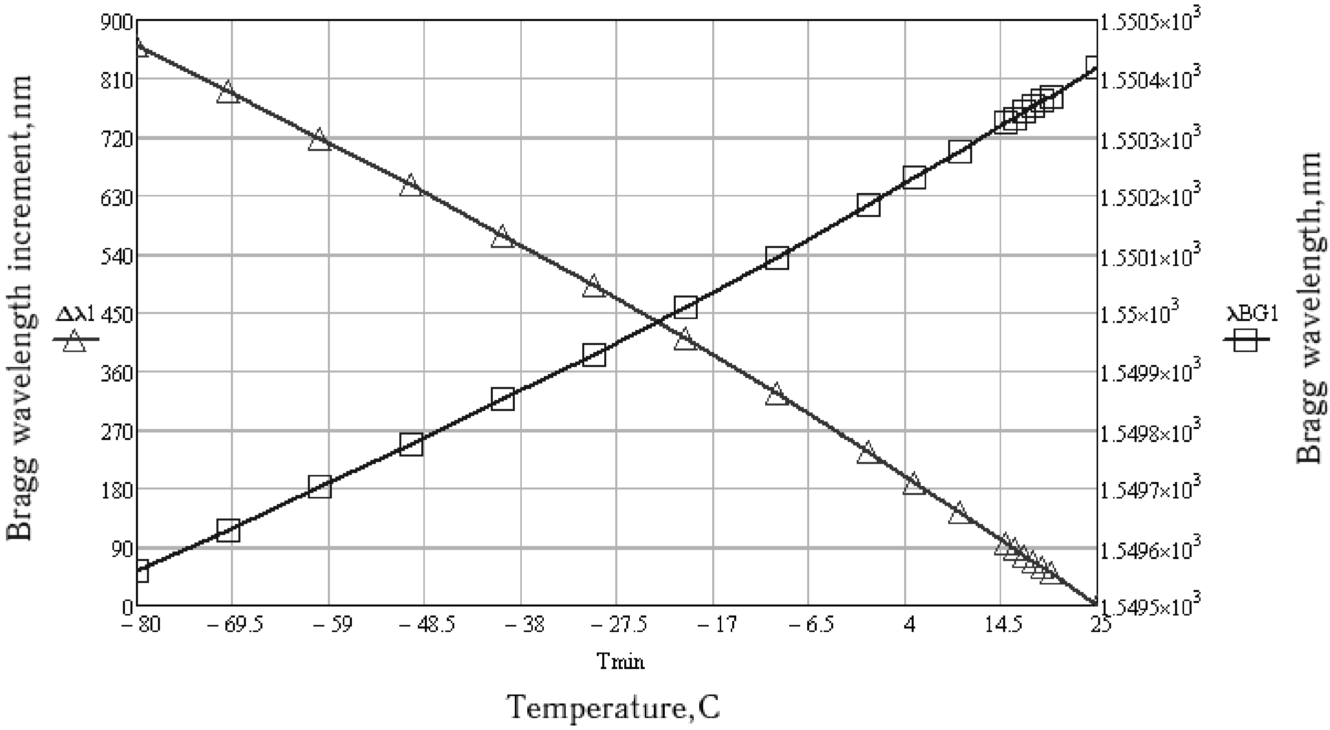


Fig. 4. Functional dependence of shift of the Bragg wavelength $\Delta\lambda_{\mathbf{BG1}}$ on temperature in the negative range

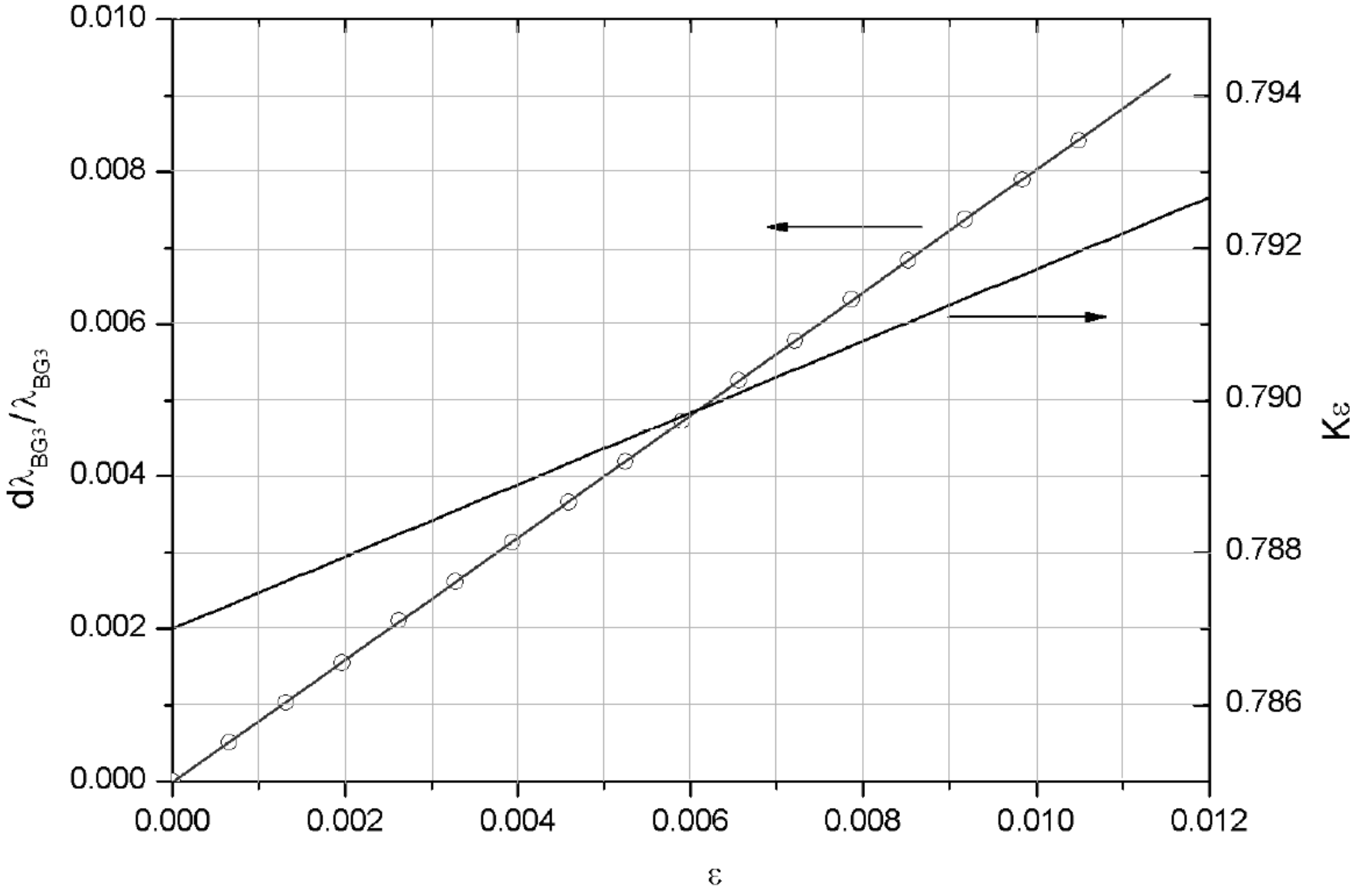


Fig. 5. Dependence of relative change of the Bragg wavelength $\Delta\lambda_{BG2}$

Dependencies $\Delta\lambda 1 = f(T_{\max})$ and $\lambda_{BG1} = f(T_{\max})$ have a linear character in all temperature range (Fig. 3). According to the formula (4), sensitivity has made 11.9 pm/°C. The analysis of experimental dependence $\lambda_{BG1} = f(T_{\max})$ has shown that sensitivity of the module in the positive range is 11.2 pm/°C. Divergence of experimental and settlement data is insignificant. As well as in case of the increased temperatures, dependences $\Delta\lambda 1 = f(T_{\min})$ and $\lambda_{BG1} = f(T_{\min})$ have a linear character in the negative temperature range (Fig. 4). Theoretically, according to the formula (4), sensitivity is 11.9 pm/°C. The analysis of experimental dependence and $\lambda_{BG1} = f(T_{\min})$ has shown that sensitivity of the sensor in the negative range is 9.1 pm/°C.

Measurement of deformation represents a certain complexity, since it demands high stability of fixing knots of a measuring part of optical fiber in the course of measurements. The dependence of relative change of wavelength on the deformation attached to optical fiber measured at normal climatic conditions is given in Fig. 5.

Experimental value of deformation coefficient $K = 0.6 \pm 0.3[1/\mu\varepsilon]$ $(K\varepsilon = 0.800 \pm 0.003[ppm/\mu\varepsilon])$ corresponds to the value of deformation coefficient received at imitating modeling $K\varepsilon = \dfrac{d\lambda_{BG2}/\lambda_{BG2}}{d\varepsilon} = 0.78[ppm/\mu\varepsilon]$.

Conclusions

The studies have shown that transformation functions $\lambda_{BG1} = f(T_{\max})$ and $\lambda_{BG1} = f(T_{\min})$ have a linear character. Sensitivity of IFMOT is 11.2 pm/°C for a positive range and 9.1 pm/°C for a negative range of temperatures. For IFMOD deformation coefficient is $K = 0.6 \pm 0.3[1/\mu\varepsilon]$.

Comparison of the indicators received at imitating modeling and experimental studies has revealed their practical full convergence that confirms efficiency of the developed information and a measuring system.

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