Monitoring of the road surface using a fiber sensor based on a fiber Bragg grid

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ABSTRACT

Currently, more and more attention is being paid to monitoring the state of road infrastructure, since it is the public domain of the country. As a result of the large flow of traffic and environmental influences, it leads to wear of the road surface. Timely detection of defects and damage to the pavement allows us to develop effective programs for maintenance and restoration of the pavement, which allows us to achieve significant costs and save time. Currently, fiber sensors are used as a more effective tool for monitoring the condition of the road surface. Since road surfaces are multilayer structures consisting of layers of granular and bituminous materials, the sensors must correspond to the heterogeneous nature and mechanical properties of the pavement materials. Fiber sensors based on the fiber Bragg grating (FBG) meet these requirements. Fiber sensors based on FBG are widely used due to advantages such as long-term stability and durability, good geometric shape, versatility, corrosion resistance, electromagnetic interference protection, low cost and high detection accuracy.

Keywords: road surface, Fiber Optics, Fiber sensors, fiber Bragg grating, damage, temperature sensors, strain sensors.

1. INTRODUCTION

Road infrastructure is one of the main state assets, as it contributes to the socio-economic development of any country. One of the most important indicators of road quality is the condition of the road surface. With increasing traffic intensity. Cracks, potholes and the consequences of bad weather, poor construction quality and lack of proper maintenance are increasingly appearing on the roads. The road surface is subject to severe wear. And the wear of the road surface is a serious problem. As in other industries, road infrastructure requires conservation, maintenance and repair. Early detection of pavement wear will prolong the service life and bring economic benefits in the maintenance of the transport network, as well as increase the level of safety and comfort of road users.

There are many procedures for assessing the condition of roads. Pavement monitoring includes visual inspection of the surface, monitoring of traffic and weather conditions, as well as measuring the pavement. This monitoring is usually carried out by the operator from a moving vehicle or using automated sensors mounted on the vehicle. For a more accurate diagnosis, the sensors can be mounted in the road surface by placing them in the middle.

In recent years, a wide variety of sensors have been developed to measure the distribution of deformations and stresses in pavement structures. The data obtained from various on-site measurements (stresses, strains, displacements, etc.) are necessary for a better understanding. The behavior of the pavement and the identification of the main mechanism of destruction, which is difficult to determine due to the variability of the pavement, temperature sensitivity and viscoelasticity of the pavement materials.

Various sensors or systems have been developed to detect damage to the road surface[1,2,3]. In [4], a non-contact measuring system based on a camera was developed to predict the destruction of the pavement,[5] a three-dimensional deformation control sensor was developed that can be installed in the asphalt pavement, [6] X-ray computed tomography was used to measure damage to asphalt material,[7] a long-period fiber grating sensor for asphalt concrete was developed pressure measurement on the road surface.

In this article, we will look at fiber sensors, which provide an additional advantage in monitoring. They allow you to identify damage before visual inspection. Since it is cheaper to maintain a road in good condition than to repair it after it

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becomes unusable, early detection of damage using sensors can optimize the maintenance plan of road services and save money.

2. MATERIALS AND METHODS

Fiber sensors are an effective tool used for monitoring and control in various information structures. These sensors can be integrated into road surfaces for continuous monitoring. Special attention in research is paid to fiber Bragg grating (FBG) sensors, which are known for high testing accuracy and can measure physical parameters distributed along the entire length of the optical fiber axis. The formation of FBG in optical fiber was first demonstrated by Hill et al. in 1978, at the Canadian Center for Communication Studies[8]. FBG is manufactured by applying intense argon-ion laser radiation to a germanium-doped fiber. BG can act as a reflector with a certain wavelength that reflects a certain wavelength of light and passes all the others. The Bragg wavelength λ_B is given by

$$\lambda_B = 2n_{eff} \cdot \Lambda, \tag{1}$$

where λ_B- is the average wavelength of the input light that will be reflected back from the fiber Bragg grating, n_{eff} - is the main refractive index, and Λ- is the grating period.

Figure 1 shows the principle of operation of a fiber sensor based on FBG.

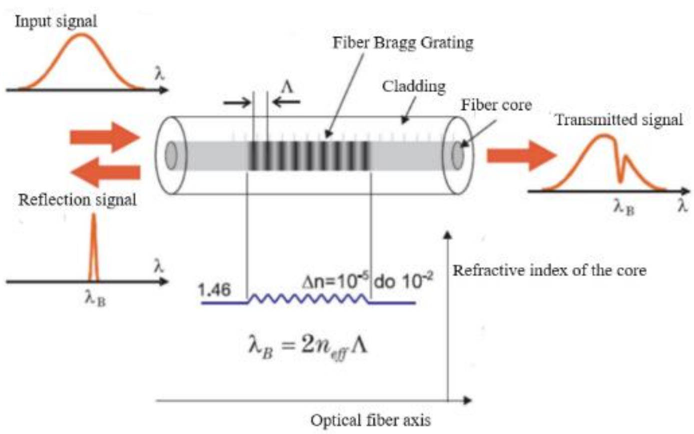

Figure 1. Principle of operation of the FBG sensor

For light with a wavelength equal to λ_B, all the reflected back partial waves are in phase with each other and constructively interfere. The reflection of light with a Bragg wavelength from FBG can reach 100%, whereas light with a different wavelength can pass almost losslessly. FBG fits into an optical fiber and the grating period depends on the voltage and ambient temperature, which makes it possible to perceive these physical quantities.

Due to the dependence of the grating period Λ on temperature and deformation, the Bragg wavelength varies depending on temperature T and deformation ε. The general expression of the strain-temperature dependence for the FBG strain sensor and the temperature compensation sensor can be described as follows [9].

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial \varepsilon} + n_{eff}\frac{\partial \Lambda}{\partial l}\right)\Delta\varepsilon + 2\left(\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right)\Delta T \tag{2}$$

The first term in formula (2) describes the effect of tensile strain on an optical fiber. It is responsible for the change in the space between the planes of the Bragg grating and for the mechanic -optical change in refractive indices. This term can be written as follows:

$$\Delta\lambda_B = \lambda_B\left\{1-\left[\frac{n_{eff}^2}{2}\left(p_{12} - v\left(p_{11} + p_{12}\right)\right)\right]\right\}\varepsilon_z \tag{3}$$

The second term in expression (2) describes the effect of temperature on the optical fiber. The Bragg wavelength is shifted due to changes in the Bragg condition under the influence of two factors: first, thermal expansion changes the distance between the grating planes; and secondly, the refractive index changes under the influence of temperature and, as a result, the optical path of the light wave changes. The main contribution to the Bragg wavelength shift is made by the second factor. This fragmentary contribution to the resonance wavelength shift can be written as:

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \quad (4)$$

Further, the temperature sensitivity of the grating can be easily obtained:

$$\frac{\Delta\lambda_B}{\Delta T} = \lambda_B(\alpha_\Lambda + \alpha_n) \quad (5)$$

where α_Λ -is the thermal expansion coefficient; α_n -is the thermo–optical coefficient.

Typical values of these parameters for optical fiber are: $\alpha_\Lambda = 0.55\cdot10^{-6}$ for fused quartz, $\alpha_n = 8.6\cdot10^{-6}$ for optical fiber with doped germanium.

3. RESULTS AND DISCUSSION

Let's test these dependencies experimentally. To accomplish this task, an installation was assembled that shows the effect of temperature in various ranges on the spectral characteristics of fiber Bragg gratings. Figure 2 shows the diagrams of the experimental stands. The presented stands and experiments on the effect of temperature and strain on the spectral characteristics of FBG were carried out in the laboratories of Optoelectronics of the Faculty of Electrical Engineering and Computer Science of the Lublin Technical University[10-16].

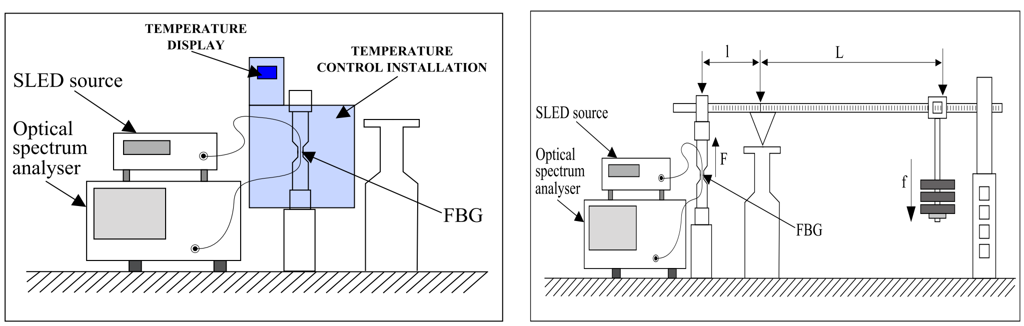

Figure 2. Structural diagrams of the experimental stand.

Let's consider the effect of temperature on the spectral characteristic of the fiber Bragg grating. The effect of temperature on the optical fiber is described by the formula (4).
Figure 3 shows the graphs obtained experimentally. The black line and the dotted line respectively show the theoretical dependence based on equation 4, and the red and blue lines correspond to the experimental result.

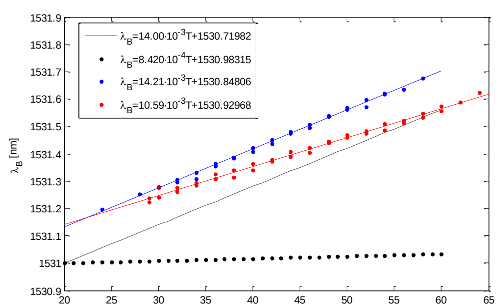

Figure 3. Dependence of the Bragg wavelength λ_B on temperature.

From the graph in Figure 3, it can be seen that the Bragg grating function is linear.

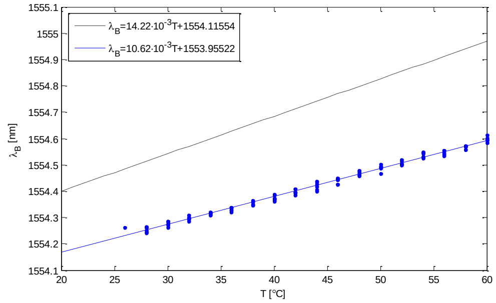

Figure 4. Dependence of λ_B = 1554.4 nm on temperature. The dotted line represents a theoretical dependence, and the solid line represents experimental characteristics.

Figure 4 shows the characteristics of the Bragg grating with a length λ_B = 1554.4 nm obtained experimentally and for comparison, the theoretical characteristics are shown. The distortion in the parameters is insignificant and amounts to 0.2 nm. Figure 5 shows the temperature dependence of the Bragg grating with a length λ_B =1566.5 nm. The sensitivity of the grating is about 0, 011 $\frac{nm}{°C}$, while the theoretical sensitivity of such a grating is 0,014 $\frac{nm}{°C}$.

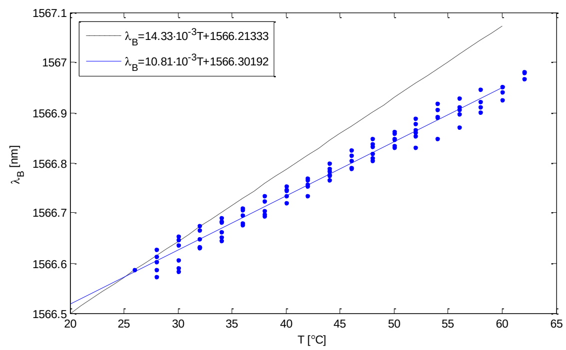

Figure 5. Dependence of λ_B = 1566.5 nm on temperature

According to the spectral characteristics obtained after the experiment, it is possible not only to track the sensitivity characteristics obtained, but also how the peak behaves during the experiment, i.e. to conduct a comparative analysis of the peak spectra by changing the size and format.
After analyzing these spectra, it can be argued that the shape and size of the peaks do not change or change slightly.
Now consider the mechanical dependence. As shown, the effect of tensile strain on an optical fiber is described by the term:

$$\Delta\lambda_B = \lambda_B[1- p_e]\varepsilon_z \quad (6)$$

Then the sensitivity characteristic will look like this:

$$\frac{\partial \Delta\lambda_B}{\partial \varepsilon_z} = \lambda_{BG}[1-p_e] = 2\Lambda n_{eff}[1-p_e] \quad (7)$$

As in the case of temperature measurements, the essence of the experiment is to identify the nature of the dependence of the shift of the resonant wavelength on the change in elongation, as well as to calculate the sensitivity to stretching.
The radiation passing through the fiber-optic path reacts to the Bragg gratings as a kind of mirror, the reflection parameters of which depend on the period of this grating. The deformation of the body rigidly connected to the fiber-optic cable leads to local compressions/stretches of the cable, and, consequently, to a change in the period of the Bragg gratings. This affects their reflective properties, which can be detected by analyzing the radiation reflected from them.

Stretching changes, the period of the Bragg gratings, which leads to a slight change in the reflective properties and a slight change in the spectral compositions of the transmitted and reflected radiation. From the above results, it can be concluded that fiber sensors based on FBG give us the opportunity to simultaneously measure various quantities. These properties of such sensors are an effective tool for monitoring systems of various structures and structures.

4. CONCLUSION

Currently, fiber sensors are widely used to monitor various structures[17-21]. The article discusses a fiber sensor based on FBG for monitoring the road surface. Monitoring of the technical condition of the road surface ensures safe operation and is the main tool for timely identification of trends in negative changes in the road surface at an early stage.

The road surface is affected by parameters such as ambient temperature and deformation from external factors. We examined the principle of operation of fiber sensor based FBG, as well as the effect of temperature and deformation on the spectral characteristics of the gratings.

Based on the results of analysis and research, it can be said that the fiber sensor based FBG can be used not only to improve the monitoring of pavement sections using the concept of an intelligent infrastructure system, but also to provide real-time data and information for the design and construction of pavement and other infrastructures.

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