Fiber optic sensor systems for non-destructive monitoring of "smart buildings"

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Abstract. The article presents the solution of the actual problem of complex monitoring of external influence parameters for urban infrastructure facilities of a “smart” city. The main characteristics of fiber-optic sensors and their sensing systems are shown. Their advantages over traditional technologies for the development of monitoring directions in “smart” cities are indicated. Solutions using fiber-optic sensor networks based on quasi-distributed systems are presented.

1. Introduction
Today, in many developed countries, new-type construction projects are being actively implemented, in which all communications and other lines in the building are controlled by an automated system. This system also assumes control of other building management functions, in particular, monitoring the state of the building, security systems, informing residents and alerting in emergency situations, as well as some other functions. These smart building management and territory projects are commonly referred “smart buildings”.

One of the fundamental principles of the system is the ability to identify specific cases that occur in the structure, and to react in a certain way to them. The functions of monitoring, receiving and transmitting various information about safety, temperature and humidity of air, lighting, water, power source, audio, video and much more, analyzing the situation depending on the settings set for it by the operator, determine the scenarios of all components of the device. However, at present, sensors are becoming more common in various fields of activity, the sensitive element of which is based on the use of fiber-optic materials, which is associated with a significant reduction in the cost of these materials, on the one hand, and on the other, with the advent of new fiber-optic materials. Therefore, it is advisable to explore the possibility of using fiber-optic sensor systems for implementation in the monitoring systems of a “smart building”.

2. Fiber-optic sensors
As part of modern systems are used as time-tested electric sensors, and high-tech fiber-optic sensors. However, at present, monitoring systems are actively developing towards the use of fully fiber-optic solutions. This direction of development is due to objective advantages over traditional sensors (Table 1).

Fiber-optic sensor structures are fiber-optic devices for detecting certain quantities, usually mechanical stress or temperature, but also displacement, vibration, pressure, acceleration, rotation, and
chemical concentration [1]. The principle of operation of such devices is that light from a certain type of optical source is passed through the optical fiber, experiencing a slight change in its parameters in the fiber or in one or several Bragg gratings, and then is determined by the detection components that evaluate these changes.

Table 1. Limits of measurement of electric and optical sensors.

| Physical quantity | Units of measurements | Measurement limit with electric sensors | Optical sensors Achieved measurement limits | Theoretical measurement limits |
|-------------------|----------------------|----------------------------------------|-------------------------------------------|-------------------------------|
| Deformation       | m                    | 10⁻⁴                                   | 10⁻¹²                                     | 10⁻¹⁴                         |
| Pressure          | P                    | 7×10⁻⁴                                 | 10⁻⁴                                     | 10⁻⁶                         |
| Temperature       | °C                   | 10⁻⁴                                   | 10⁻⁶                                     | 10⁻⁸                         |
| Rotation          | deg/h¹/₂             | 10⁻⁴                                   | 10⁻⁴                                     | 10⁻⁸                         |
| Acceleration      | m/s²                 | 10⁻⁶                                   | 10⁻⁷                                     | 10⁻¹²                        |
| Magnetic field    | T                    | 10⁻²                                   | 10⁻²                                     | 10⁻⁴                         |
| Electric field    | V/m                  |                                        |                                          |                              |

Automated monitoring systems can be implemented at the facility both at the construction stage and at the commissioning stage. Sensors have various mounting methods: they can be located on the surface, be embedded in the structure of an object, be in a humid environment, and other difficult conditions.

There are various types of fiber-optic sensors (Figure 1) that are used in monitoring systems.

![Fiber optic sensors classification](image)

**Figure 1.** Fiber-optic sensors classification.

Fiber optic sensors are often implemented on fiber Bragg gratings (FBG). The basic principle of the main fiber-optic sensors lies in the dependence on the Bragg center wavelength in the array, not only on the grating period, but also on the mechanical effect and temperature.

There are several publications on the use of FBG as sensors for temperature, mechanical stress, and measurement of the external refractive index [2-4]. Typical values of $\lambda_{BG}$ shift as a function of the temperature are 0.01 nm/°C, as a function of the relative elongation of the optical fiber $\approx 10^3 \times \Delta L/L$ nm.
3. **Quasi-distributed FBG array probing system**

Some fibers may contain a number of sensor arrays to control temperature and strain throughout the fiber. This is called quasi-distributed probing. FBG sensors are very suitable for detection and data collection, where sensor arrays can be multiplexed using similar methods that have been applied to fiber optic sensors, such as wavelength division multiplexing (WDM), spatial division multiplexing (SDM) and time multiplexing (TDM), since they can be directly implemented in the fiber without changing the fiber diameter. This feature makes FBG sensors suitable for a wide range of applications.

Thus, there is an urgent task of developing a sensor-based monitoring system for FBG arrays. Key requirements are measurement accuracy, the ability to increase the number of sensors, low cost and ease of manufacture, and reliability.

Based on the traditional solution of a «broadband light source – an array of FBG – spectrometer», we have developed a different approach to polling systems of sensor arrays (Figure 2).

**Figure 2.** Fiber-optic sensors system with FBGs broadband triangle filter. T – temperature, S – strain, RI – refractive index.

As a signal source, we used a widespread broadband light source. It probes several channels (up to 16) of FBG sensors, which are connected in series (up to 16, depending on the measurement range). The array of sensors is shown in Figure 3 (8 sensors are used).

**Figure 3.** FBG sensor array on 1 measuring channel (a), FBG sensor array after probing (b).
To determine the direction of displacement of each FBG with dependence on external influence, we used FBG with an asymmetric triangular shape of the spectral characteristic. This form provides a wide linear slope of the spectrum in the absence of measurement duality.

To form the required spectral profile of an asymmetric triangular FBG, it is necessary to use a femtosecond laser and a step-by-step recording method with a certain law of change in the refractive index, apodization coefficient and chirping ratio in each FBG region (Figure 4).

![Figure 4. FBG characteristics with a triangular spectrum shape.](image)

For the formation of a fiber-optic broadband sawtooth filter, we use a FBG sequence with a triangular shape of the spectrum in the required wavelength range (Figure 5). Each grating in the filter is tuned to the spectral region of the corresponding FBG sensor with regard to the measurement range.

![Figure 5. FBGs filter spectrum shape.](image)

When temperature or mechanical tension changes, the sensitive element of the sensor array reacts to this effect and shifts along the wavelength. Depending on the direction of shift, the power level from the sensor after passing through the filter increases or decreases. Thus, it is possible to make an unambiguous conclusion about the magnitude of external influence.

Having one special structure of the optical filter, we can use many typical FBG sensors. Such a simple solution solves the problem of improving the technical and economic characteristics of fiber-optic sensor systems and can be used in monitoring systems of smart buildings.
4. Conclusion

Bragg fiber grating based sensor systems are well suited to detect and record critical characteristics of the structural response, as well as environmental performance, which lead to degradation. FBG deformation sensors are useful in the process of assessing the response to stressful influences, such as motion, wind, earthquakes, explosive phenomena, clearing supports, etc. FBG sensors are also ideal for monitoring weather conditions, such as trapped moisture in asphalt pavement systems, since they are often the main cause of rapid degradation.

The structural integration of the Bragg fiber-optic sensors and fiber-optic sensor systems represents a new branch of engineering and is a major breakthrough in creating the infrastructure of intelligent cities. Currently, Bragg fiber grating sensors are a fundamental and indispensable component of any intelligent control system for a fiber-optic system. A well-functioning control system is usually equipped with an FBG sensor array that allows this system to collect and process the necessary environmental data. After collecting data, the fiber-optic system is able to fully characterize its environment and adjust its operations accordingly.

In this paper, a combined FBG survey method has been developed, which makes it possible to probe the complex topologies of sensors of different directions (temperature, mechanical stress). Computer simulation of the sensing system was performed, the results of a survey of the sensor array were obtained. The methodical recommendations on the application of this method for various objects of urban infrastructure are given.

The development of technologies of fiber-optic materials, the theory and practice of the use of fiber-optic sensors suggests that in the coming years, the results presented in the work can be realized practically.

Acknowledgements

This work was supported by a grant from the President of the Russian Federation for state support of young Russian scientists - candidates of sciences MK-3421.2019.8 (agreement No. 075-15-2019-309) and Ministry of Education and Science of Russian Federation (8.6872.2017/BCh, program “Asymmetry”)

References

[1] Grattan K T V and Sun T 2000 Sens. and Act. 82 40
[2] Aybatov D L, Morozov O G and Kiyamova R R 2000 Proc. of SPIE 7374 73740B
[3] Denisenko P E, Denisenko E P and Morozov O G 2011 Proc. of SPIE 10342 1034217-1
[4] Davis M A and Kersey A D 1996 Proc. of SPIE 2838 114