Modelling and record technologies of address fiber Bragg structures based on two identical ultra narrow gratings with different central wavelengthes

O.G. Morozov[1], A.Zh. Sakhabutdinov[1], I.I. Nureev[1], R.Sh. Misbakhov[2]

[1]Kazan National Research Technical University n.a. A.N. Tupolev-KAI, Karl Marx street 10, Kazan, Russia, 420111
[2]Kazan State Power Engineering University, Krasnoselskaya street 51, Kazan, Russia, 420066

Abstract. Address fiber Bragg structures (AFBS) make it possible to effectively solve the problem of sensors interrogation and multiplexing in multi-sensor networks with microwave photonic processing of information. Based on the method of inverse Fourier transform, a mathematical model of the optical fiber refractive index profile was constructed to form 2λ-FBG AFBS with two FBG with identical spectral responses at separated wavelengths. As the initial parameters for the construction of the mathematical model, the desired spectral profile of 2λ-FBG AFBS was specified, including the reflection coefficient and the width of the transmission band of its two identical ultra-narrow-band gratings and the separation between them. On the basis of the study of the mathematical model, the possibility of selecting the necessary values of the refractive index and the laws of its modulation is shown, allowing the spectral profile of 2λ-FBG AFBS to be formed so that they can be used as a sensitive element, transforming information from optical range to radiofrequency one. The analysis of the formation and recording methods for 2λ-FBG AFBS was carried out. To implement given structures, the technology, using of an ultraviolet argon laser, the classic phase masks with sequential recording of several arrays with precise movement and strain of the fiber were chosen.

1. Introduction

The article discusses a possibility of using fiber-optic sensors based on addressed fiber Bragg structures (AFBS) to assess any object dynamics in real operating conditions. The motivation of investigation is a fact that a complete and satisfactory theory of an object dynamics and an economically probing sensor for measuring forces acting in a contact patch have not yet been developed. A description of the new technology of multisensor measurements of continuous monitoring of an object state is presented. The experimental device sensors are based on use of AFBSs with two identical ultra-narrow-band reflection spectra (2λ-FBG). Information from the sensors is used as input parameters of algorithms, which allow to estimate key characteristics of an object. One of advantages of this new technology in comparison with analogues is a fact that an optical photodetector is used as an interrogator, which greatly simplifies the system.

2. General description of measuring system

The proposed system is based on the use of the address fiber Bragg structures (AFBS) with two identical ultra-narrowband responses in the amplitude-frequency plane (2λ-FBG) [1, 2] with microwave photonic interrogation methods. Microwave photonic interrogation methods have a high data transfer rate and the ability to use the array of AFBS sensors for different connection topologies [3].

Key elements that contribute to the success of the proposed technology in this area include the relative ease of installation of sensors and interrogation equipment, the use of sensors of small dimensions and weight (up to 5 g), the use of a simple and low-power power source of low weight, and the possibility of obtaining a reliable measuring signal with sensors.

The article justifies the choice of the type of optical sensor and provides its description and installation method; describes how to find the characteristics of the object dynamics in the contact patch; mathematical models of the optical sensor and the object were investigated, where the main focus of the research is on the mathematical definition of phenomena in the contact patch of the object and media; presents a method for interrogation of optical sensors; similar solutions were reviewed and compared, providing opportunities for analyzing object dynamics.

3. Measuring system structure on 2λ-FBG sensors

The fiber optic AFBS pressure and temperature sensors based on the 2λ-FBG structures are installed on or in the object and record pressure and temperature values at one point of the contact patch. The presented optoelectronic circuit of the AFBS survey (Figure 1) is based on principles of microwave photonic measurements and is intended to analyze the radiation reflected from two AFBS sensors.

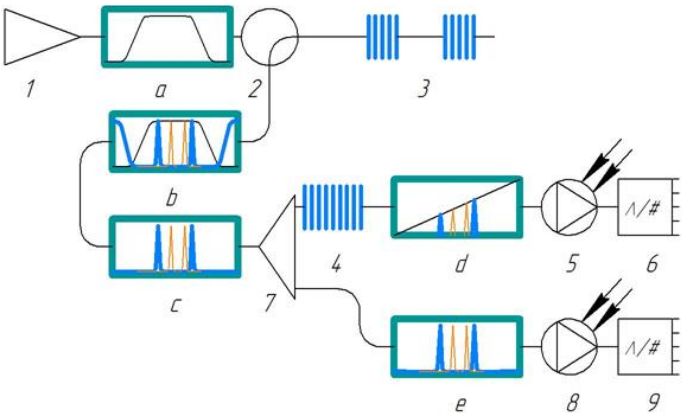

Figure 1. The 2λ-FBG sensor interrogation scheme.

A wideband laser source - 1 generates continuous laser radiation, which is reflected from two AFBS - 3. A circulator - 2 redirects the signal reflected from two AFBS (diagram b) to a fiber optic splitter - 7, which divides the optical signal into two - reference and measuring. In the measuring channel, a filter with a linear amplitude-frequency characteristic is installed - 4, asymmetrically changing the amplitudes of four-frequency radiation (scheme d), after which the optical signal is fed to a measuring photo detector - 5 and received on an analog-digital converter (ADC) - 6. In the reference channel, the signal (scheme f), without changing a power, hits the reference photodetector - 8 and is received in the reference ADC - 9. All further calculations are not carried out with the absolute value of a luminous flux, but with the power ratio measuring and control channels.

The ratio of the powers of the optical signal at the photodetectors - 5 and 8 - makes it possible to eliminate a drawback associated with fluctuations in the power of the light flux arising in an optical-electronic system. The signal by the method of address frequency (analog or digital) filtering is used to determine the position of the AFBS [3].

The use of the AFBS, the linear oblique filter coupled with the photodetector, as an interrogator has several advantages relative to optical-electronic polling circuits based on the frequency sensing of the spectral response due to the high polling rate and higher measurement accuracy [4]. Microwave photonic interrogation methods of AFBS eliminates the measurement system from the use of expensive narrow-band lasers or optical filters with a wide frequency tuning range or the use of complex interferometric methods with highly sensitive equipment for interrogation an array of sensors with the same central wavelength. Compared with microwave photonic polyharmonic probing, the proposed approach eliminates the need to use optical code division, which uses an array of sensors probed with a Slepian pseudo-random binary sequence to correlate the reflected signal from each sensor with an instantaneous code, which greatly simplifies the interrogation of sensors.

4. Simplified mathematical model of measuring system

The temperature of the tire at the point of installation of the AFBS sensor can be determined as a function of temperature as a function of a shift of a center wavelength for the temperature sensor [5].

$$T = f(\Delta\lambda_T, c_2, c_1, c_0) = c_2 \cdot (\Delta\lambda_T)^2 + c_1 \cdot \Delta\lambda_T + c_0\ , \tag{1}$$

where $\Delta\lambda_T$ is the central wavelength offset for the temperature sensor, c_0, c_1, c_2 are calibration coefficients for temperature dependence on the central wavelength offset.

Measurement of pressure acting on the sensor can be represented as a function depending on the displacement of the central wavelength for the pressure sensor and the temperature sensor.

$$P = f(\Delta\lambda_T, \Delta\lambda_P) =$$
$$\begin{cases} c_{2,3} \cdot {\Delta\lambda_T}^2 \cdot {\Delta\lambda_P}^3 + c_{2,2} \cdot {\Delta\lambda_T}^2 \cdot {\Delta\lambda_P}^2 + c_{2,1} \cdot {\Delta\lambda_T}^2 \cdot \Delta\lambda_P + c_{2,0} \cdot {\Delta\lambda_T}^2 + \\ +c_{1,3} \cdot \Delta\lambda_T \cdot {\Delta\lambda_P}^3 + c_{1,2} \cdot \Delta\lambda_T \cdot {\Delta\lambda_P}^2 + c_{1,1} \cdot \Delta\lambda_T \cdot \Delta\lambda_P + c_{1,0} \cdot \Delta\lambda_T + \\ +c_{0,3} \cdot {\Delta\lambda_P}^3 + c_{0,2} \cdot {\Delta\lambda_P}^2 + c_{0,1} \cdot \Delta\lambda_P + c_{0,0} \end{cases} , \tag{2}$$

where $c_{i,\ k}$ are calibration factors that should be determined on a calibration bench for various combinations of temperatures and pressures. The dependence [3] is calibrated using the least squares method.

Let us designate the requirements for the measuring system and the 2λ-FBG profile, which will allow using the 2λ-FBG structure (or an array of 2λ-FBG structures) as sensitive elements of the measuring system.

First, it is necessary to ensure the possibility of polling the characteristic features of the 2λ-FBG structure - responses from two identical ultra-narrow-band FBGs - over the entire measuring range. Secondly, that the light response only from the address frequencies of the 2λ-FBG structure falls into the study area [1].

Meeting the requirements is ensured by building a measuring optic-electronic circuit. Let us include in the measuring circuit a laser source with a frequency range equal to a measuring range and apply a band-pass optical filter that transmits only the required frequency range, thus avoiding the ingress of an extraneous - not from two address frequencies 2λ-FBS structures - radiation in the signal analysis region. Note that, as a band-pass filter, a wide FBG with an amplitude-frequency form close to rectangular, superimposed directly after the laser source, can be successfully used. The technical possibility of simulating FBG with a given shape of the spectrum is well described in works [6, 7]. Thus, both method requirements are fulfilled

5. 2λ-FBG AFBS writing technology

The analysis of the formation and recording methods for 2π-FBG AFBS was carried out. The addressed 2π-FBG structure consists of three sequentially formed FBGs with π-phase shifts between them. To implement given structures, the technology, using of an ultraviolet argon laser, the classic phase masks with sequential recording of several arrays with precise movement of the fiber were chosen.

6. Conclusion

The proposed measuring system is based on the theory and technology of targeted microwave photonic measurements, which allows estimating the parameters of pressure and temperature in the contact patch in real time, and on the basis of these data, approximate the key parameters of the dynamics of the contact patch of the object. As shown in the work, the measuring system can be significantly expanded through the use of a larger number of sensors, which further opens up the possibility to evaluate the full object dynamics in the contact patch. The high speed of data acquisition and processing allows building a plot of dynamic pressure at the point of sensor installation, and, consequently, with higher resolution, to determine the characteristics of forces in the contact patch with high accuracy. The use of a dual temperature and pressure sensor allows to take into account the influence of temperature, and has the potential to develop a model of object dynamics.

The results of the application of the 2λ-FBG in different areas confirm the potential of the selected sensors, which provide signals with high resolution and accuracy, do not require a powerful energy source or complex transmission systems and are capable of operating in various adverse conditions.

The reliability of the optoelectronic measuring circuit and the experimental setup developed allows for the expansion of research directions.

7. References

[1] Morozov, O.G. Radiophotonic method for instantaneous frequency measurement based on principles of frequency-amplitude conversion in fiber Bragg grating and additional frequency separation / O.G. Morozov, A.A. Ivanov, V.A. Andreev // XI IEEE International Conference on Antenna Theory and Techniques (ICATT). – Ukraine, Kyiv, 2017. - P. 427-430.

[2] Khabibullin, R.A. Two-frequency radiation forming on chirped FBG for tuning terahertz carriers generation / R.A. Khabibullin, O.G. Morozov, A.J. Morozov, A.Jh. Sakhabutdinov, A.A. Kuznetsov // IEEE Systems of Signals Generating and Processing in the Field of on Board Communications, 2018. – P. 1-4.

[3] Sakhabutdinov, A.Zh. Universal Microwave Photonics Approach to Frequency-Coded Quantum Key Distribution / A.Zh. Sakhabutdinov, O.G. Morozov, G.A. Morozov [Electronic resource]. – Access mode: intechopen.com/books/advanced-technologies-of-quantum-key-istribution/universal-microwave-photonic-approach-to-frequency-coded-quantum-key-distribution.

[4] Sakhabutdinov, A.Zh. Fiber Bragg grating length as sensing parameter: new way for fibre optic wear sensor / A.Zh. Sakhabutdinov, O.G. Morozov, A.A. Kuznetsov // Proc. SPIE. – 2018. – Vol. 10774. – P. 107741G.

[5] Sakhabutdinov, A.Zh. Calibration of combined pressure and temperature sensors / A.Zh. Sakhabutdinov, I.I. Nureev, A.A. Kuznetsov // International Journal of Applied Engineering Research. – 2015. – Vol. 10(24). – P. 44948-44957.

[6] Bourdine, A.V. Fiber Bragg grating writing technique for multimode optical fibers providing stimulation of few-mode effects in measurement systems / A.V. Bourdine, O.G. Morozov, I.I. Nureev // Proc. of SPIE. – Vol. 9807. – P. 98070J.

[7] Ricchiuti, A.L. Microwave Photonics Filtering Technique for Interrogating a Very-Weak Fiber Bragg Grating Cascade Sensor / A.L. Ricchiuti, J. Hervás, D. Barrera, S. Sales, J. Capmany // IEEE Photonics Journal. – 2014. – Vol. 6(6). – P. 1-10.

Acknowledgments

The work was carried out with the financial support of the Ministry of Education and Science of the Russian Federation within the framework of the basic part of the Kazan National Research Technical University named after A.N. Tupolev-KAI state task 8.6872.2017/8.9 and within implementation of the federal special program «Research and development in the priority directions of development of scientific and technological complex of Russia for 2014-2020», the agreement on granting a subsidy № 14.574.21.0188, unique identifier of applied scientific research (project) RFMEFI57418X0188.