Modelling and record technologies of address fibre Bragg structures based on two identical ultra-narrow gratings with different central wavelengths

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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. Further paper deals with issues of interrogation of the developed structures and principles of measurement system construction on their basis.

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 address multi-sensor measurements of continuous monitoring of an object state is presented.

In search of a solution to address measurement problem, the authors paid attention to the spectral-coded FBGs [1-5] and FBGs with two π-phase shifts [6-8]. Spectral-coded FBGs allow a complete separation of responses from few sensors operating on the same central wavelength. However, the
interrogation of such systems requires a source of dual-frequency scanning radiation and an electronic vector analyzer for additional calculations.

FBGs with two $\pi$-phase shifts had nothing to do with the problem of the interrogation of overlapping sensors multitude. In the paper [6] they were used to integrate and differentiate optical pulses, in the paper [7] – to generate a pair of carriers, in the paper [8] – to shape pulses. However, the possibility of the difference frequency rearrangement between phase shifts in them in order to change parameters of functional transformations, suggested the possibility of creating address sensors on their basis. The address parameter, discriminating sensors, may be the width of the frequency/wavelength separation between phase shifts. Processing information about the Bragg wavelength shift at the difference frequency, determined by the frequency difference between the phase shifts, will allow us to construct a sensor system with a unique response from each grating.

There are at least two theoretical approaches to a formation of the AFBS with the invariant distance between its address frequencies under the influence of measured fields on it. The first approach is the use of fiber Bragg gratings (FBGs) with two symmetric phase $\pi$ shifts ($2\pi$-FBGs), and the second is the use of two identical ultra-narrow FBGs separated by wavelength ($2\lambda$-FBG). In second case, the address parameter, discriminating sensors, may be the width of the frequency/wavelength separation between ultra-narrow FBGs. Processing information about the Bragg wavelength shift at the difference frequency, determined by the frequency difference between given gratings, will allow us to construct a sensor system with a unique response from each grating.

The experimental device sensors are based on use of AFBSs with two identical ultra-narrow-band reflection spectra FBGs ($2\lambda$-FBG) at separated wavelengths. Information from the sensors is used as input parameters of algorithms, which allow to estimate key characteristics of a sensor and a system. 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.

Further article is constructed as follows. In the second part, the problems of AFBS with two identical ultra-narrow-band reflection spectra FBGs ($2\lambda$-FBG) at separated wavelengths modeling are considered and the main parameters of sensors based on them are determined. The third part analyzes the methods of recording and forming such structures in the fiber. The following parts deal with issues of interrogation of the developed structures and principles of measurement system construction on their basis.

2. Modelling $2\lambda$-FBG AFBS and forming sensors based on them

Among various methods for the synthesis of FBG, the Fourier transformation (FT) is successfully used in cases, when the defining functions are the period and depth of modulation of the refractive index of the fiber. As a rule, the FT consists of determining the parameters of amplitude and phase, which can be separated and applied onto the fiber core independently. The idea of forming an arbitrary FBG spectral form is based on the fact that the FBG modulation coefficient is the inverse Fourier transform of the reflection spectrum of the grating. The profile of the expected spectrum can be approximately described mathematically by the function.

The inverse FT can set the amplitude to determine the modulation coefficient. As a rule, after the FT we obtain a discrete phase, we can also construct a phase modulation of the grating along the axis, which is the optical axis in the fiber. Thus, the relationship between the FBG contour profile and the envelope of the modulation index of the refractive index of the fiber is expressed by the relation:

$$ F(z) \exp(j\theta) = \int_{-\infty}^{\infty} F_\beta \exp(j\beta z) d\beta, $$

where $\beta$ is the spatial frequency, $z$ is the coordinate along the fiber length, $F(z)$ is the modulation coefficient of the envelope, $\theta$ is the modulation phase in FBG, $F_\beta$ is the spectral form. By specifying the
spectral form $F_{\beta}$, the inverse FT yields the dependence of the modulation intensity $F(z)$ of the signal along the fiber.

FT method is one of the simplest approaches for modeling $2\lambda$-FBG, but for large reflection coefficients of the grating, this method introduces significant errors. In [9], it was proposed to use the coupled mode method in conjunction with the Fourier transform.

We write the transfer matrix for the $2\lambda$-FBG structure in the form [9]:

$$
\begin{bmatrix}
R_{L/2} \\
S_{-L/2}
\end{bmatrix}
= F_{m}G_{m}F_{m-1}G_{m-1}...F_{1}G_{1}
\begin{bmatrix}
R_{-L/2} \\
S_{L/2}
\end{bmatrix}
. \tag{2}
$$

Central segment $F_{i}$ have to introduce phase shift equal to $\pi$.

Having set of the required $2\lambda$-FBG spectral form, we obtain the parameters of the design of the FBG with two identical frequency responses instead of one. To simulate $2\lambda$-FBG, the OptiGrating 4.2 software package was used with the use of an algorithm for solving the inverse problem of forming a FBG form with given spectral characteristics.

We assign the desired spectral form $2\lambda$-FBG, which is a two-frequency radiation with a differential address frequency of 31.25 GHz (~250 pm). Each frequency component is modeled by a Gaussian curve.

Figure 1a shows the required spectrum of $2\lambda$-FBGs, and in the upper part the equation of its curve is mathematically described. The resulting spectrum of $2\lambda$-FBG is shown in figure 1b.

We note that the required and real spectra of $2\lambda$-FBGs will never coincide completely with each other. In the course of the research, it was not possible to achieve the results of modeling of a $2\lambda$-FBG structure with a width of spectral response lines close to those occurring in a $2\pi$-FBG. Despite the fact that the width of the spectral response lines of $2\lambda$-FBG has a correlating dependence with the length of the simulated $2\lambda$-FBG, this dependence is very weak. And even a strong increase in the length of the modeled $2\lambda$-FBG structure does not lead to a significant decrease in the spectral width of the response lines, and the use of super-long sensitive elements in the technique is rather difficult, although it can be used for some class of problems.

3. $2\lambda$-FBG AFBS record technology
The analysis of the formation and recording methods for $2\pi$-FBG AFBS was carried out [10-15].
As can be seen from [10-15], 2λ-FBG structures can be obtained using a standard ultraviolet laser and using nanometer shifts. In this case, both the phase mask and other interferometric schemes can be used. The papers [10, 14] presents the method of recording the AFBS using the mechanical tension of an optical fiber. Record of 2λ-FBG is conducted using a phase mask. To adjust the position of the phase shift, a motorized movement is used, realizing the movement of the phase mask and a spring, which induces mechanical stress on the fiber. The authors of the technology obtained two identical FBGs with a spacing of 1 nm and a bandwidth of 0.3 nm [14].

We have obtained narrower grating bandwidths, which amounted to 110 pm. This bandwidth is also too large and leads to significant errors in the measurement estimate. The width of the bandwidth can be reduced by increasing the length of the lattice. In this case, the length of the AFBS was 1.5 cm; its increase to 3 cm, allowed to obtain a grating with a width of 45 pm.

In papers [11-13], a method for recording 2λ-FBG structures is presented by alternating sections with an induced grid and “empty” fiber sections. The recording was made with the help of a fixed phase mask along which the fiber moved to the specified length. At certain points in time, the ultraviolet beam was disconnected. Parameters of 2λ-FBG can be easily rebuilt by changing the step of movement. The wavelength spacing between the two peaks was 0.7 nm, and the transmission bandwidth was 100 pm. In the development of this method, the authors proposed cascading the inclusion of structured FBGs and obtained a bandwidth of 1 pm, which fully meets the requirements for AFBS for solving precision problems.

We have demonstrated the possibility of recording FBG with two identical ultra-narrow-band reflection spectra FBGs using last technique for different applications [16-20] and for AFBS especially on the equipment of the R&D Institute of Applied Electrodynamics, Photonics and Living Systems of KNRTU-KAI n.a. A.N. Tupolev, and positioners with much lower accuracy (± 0.1 micron) were used to displace the fiber. Thus, the use of 2λ-FBG structures obtained using classical phase masks may be limited to application in single or low sensory applications, in which it is not the measurement of the magnitude itself that is important, but its abrupt change. To use 2λ-FBG structures in precision measurement systems, it is necessary to use the recording technology of structured FBGs in which the grating bandwidth can reach 1 pm and less, especially when cascaded.

4. 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) with microwave photonic interrogation methods [21-23]. Microwave photonic interrogation methods have a high data transfer rate and the ability to use the array of AFBS sensors for different connection topologies.

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.

5. 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 2) is based on principles of microwave photonic measurements and is intended to analyze the radiation reflected from two AFBS sensors.
Figure 2. 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 photodetector – 5 and received on an analog-digital converter (ADC) – 6. In the reference channel, the signal (scheme e), 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 [23].

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 interrogation rate and higher measurement accuracy. 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 poly-harmonic 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.

6. Basics of the measurement method
In order for AFBS to be used as MWPSS sensitive elements, two additional conditions must be met. The first condition is that the region of the light flow analysis must include the response from only two frequencies of each AFBS that form their address. The second condition is that the AFBSs that have the same central (Bragg) frequency must have different address frequencies.

The approach to determination of the central (Bragg) frequency shift is based on the optical conversion of the resulting signal from AFBS in a linear oblique filter with a sloped amplitude-frequency characteristic, and an optoelectronic conversion of the optical signal to the microwave frequency band on the photodetector. After that, the system of nonlinear equations obtained by the address frequency filtering of the resulting signal after the photodetector is solved.

The shape of the spectral response of the AFBS in the amplitude-frequency plane after the filter with an inclined amplitude-frequency characteristic is shown in figure 3.
There the following notation is used: \( \omega_C \) is the central (Bragg) frequency of the AFBS; \( \omega \) is the frequency of the left spectral component; \( \delta \) is the full width at half the height of the frequency components forming the address; \( \Omega \) is the address frequency; \( u \) and \( v \) are the parameters of a linear oblique filter. The optoelectronic probing scheme of a single AFBS likes to shown in figure 2.

The shift of the AFBS central (Bragg) frequency leads to a change in the ratio of the amplitudes of the two-frequency response from the AFBS, which leads to the change in the modulation depth and amplitude of the oscillations of the two-frequency beat of the AFBS at the photo-receiver.

The equation of the two-frequency beating envelope of the resulting response from the AFBS on the photodetector depends on the amplitudes of the left and right frequency components and is expressed as follows:

\[
S(t, \omega_C) = A^2 + B^2 + 2AB \cos(\Omega t + \phi),
\]  

where \( A \) is the amplitude of the left and \( B \) – of the right frequency components that form the address, which depend on the position of the central (Bragg) frequency of the AFBS: \( A = A(\omega_C) \) and \( B = B(\omega_C) \); \( \phi \) is the phase difference of the optical carriers. The modulation factor of the beating envelope (3) can be used as the only measurable parameter to determine the center (Bragg) frequency of the AFBS:

\[
M(\omega_C) = \frac{2 \cdot A(\omega_C) \cdot B(\omega_C)}{A^2(\omega_C) + B^2(\omega_C)}.
\]  

The modulation coefficient of the envelope (4) is a monotonic function that depends on the shift of the central (Bragg) frequency of the AFBS (figure 4). Consequently, there is an inverse function \( \omega_C(M) \), which allows one to determine the offset of the AFBS Bragg frequency from the known value of the modulation coefficient.

The main requirement is that the dependence of the modulation coefficient on the shift of the central (Bragg) frequency of the AFBS must be determined in advance with the known parameters of the oblique filter for each of the AFBS.

Despite the fact that the modulation factor dependency on the central frequency of the AFBS is monotonous and allows solving the problem of determining the offset of the central frequency of the AFBS under the influence of physical fields, and, as a result, determining the magnitude of this effect, it does not ensure uniformity of the measurement scale.
In addition, it is necessary to ensure the independence of the measurement information from fluctuations in the power of the light flux on the photodetector that are not related to the action of the measured physical fields.

In order to linearize the measurement scale, you can use filters with non-linear amplitude-frequency characteristic. For example, filters with amplitude-frequency characteristic obeying a power law or, for example, filters with an exponential profile shape:

$$L(\omega) = e^{C(\omega/\omega_{\text{Max}})^n} - 1,$$

where $\omega_{\text{Max}}$ is the maximum value of the measurement range, and $n$ and $C$ are the filter parameters.

When using nonlinear filters, the lack of unevenness of the measurement scale is leveled. Another option for improving the resolution of the measurement scale is the possibility of superimposing two opposite oblique filters in different arms of the reflected signal and to take measurements in the shoulder with higher signal level.

To avoid fluctuations of the power of the light flux on the photodetector that are not related to the effect of physical fields, it is proposed to normalize the power of the light flux by creating two channels: a reference one without an oblique filter and a measuring one with an inclined filter modulation (5) normalized to full power in the reference channel.

In the framework of the proposed optoelectronic circuit, it is necessary to solve the additional problem of temperature stabilization of a filter with an inclined frequency characteristic in order to avoid signal distortions associated with its temperature drift. The problem of temperature stabilization of the filter is solved by a corresponding standard method and is not considered in the framework of this work.

The usage of two (or more) AFBSs with the same central (Bragg) frequency in the measuring system has several advantages. First, it significantly reduces the requirements for the operating frequency range of all the optical components of the system. Secondly, as a result, it leads to a significant reduction in the cost of the components used. Third, it is the way to unify the components of the sensory system. At the same time, additional difficulties arise in determining the central (Bragg) frequencies of the AFBSs in the array of sensors, since the system produces multiple cross-beats of all the frequency components that form the address frequencies of the AFBSs.

The measuring system does not impose any additional restrictions on the mutual distribution of the AFBS array in the entire measurement range; therefore, all possible combinations of cross-beats of all
frequency components forming the AFBS addresses will occur on the photodetector. In addition, both repetitive and multiple beat frequencies to the address frequencies of the AFBS can occur in the system, which complicates the search and identification of their central frequencies.

Despite this, a method for processing of an complex signal received from the AFBS array with the same central frequency and different difference frequencies was found, which allows to solve the problem of determination of all AFBS central frequencies positions in the sensor array. Narrowband filtering of the complex signal at the address frequencies of AFBS sensors array allows to obtain a system of equations, which makes it possible to determine the position of the central (Bragg) frequencies of all of the AFBS in the array:

\[
\begin{align*}
\sum_{i=1}^{N} \sum_{k=1}^{N} \left( \frac{(\Omega_j - [\Omega_k - \Omega_0])^2}{2\sigma^2} + \frac{A_i A_k e}{2\sigma^2} + \frac{A_i B_k e}{2\sigma^2} + \frac{B_i A_k e}{2\sigma^2} + \frac{B_i B_k e}{2\sigma^2} \right) &= D_j, \quad j = 1, N, 
\end{align*}
\]

where \( D_j \) is the amplitude of the signal at the frequency \( \Omega_j \), the factor with the exponent at each term describes the frequency filter at the address frequency at the frequency \( \Omega_k \).

The system of equations (6) can be solved only numerically. The most suitable method for solving the systems of equations of this class is the iterative methods of the modified Newton-Rafsson method or the Levenberg-Marquardt method, which have quadratic convergence.

7. 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 [23].

\[
T = f(\Delta \lambda_T, c_2, c_1, c_0) = c_2 \cdot (\Delta \lambda_T)^2 + c_1 \cdot \Delta \lambda_T + c_0, \quad (7)
\]

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:

\[
P = F(\Delta \lambda_T, \Delta \lambda_p) = \begin{cases}
c_{2,3} \cdot \Delta \lambda_T^2 \cdot \Delta \lambda_p^3 + c_{2,2} \cdot \Delta \lambda_T^2 \cdot \Delta \lambda_p^2 + c_{2,1} \cdot \Delta \lambda_T^2 \cdot \Delta \lambda_p + c_{2,0} \cdot \Delta \lambda_T^2 + \\
c_{1,3} \cdot \Delta \lambda_T \cdot \Delta \lambda_p^3 + c_{1,2} \cdot \Delta \lambda_T \cdot \Delta \lambda_p^2 + c_{1,1} \cdot \Delta \lambda_T \cdot \Delta \lambda_p + c_{1,0} \cdot \Delta \lambda_T + \\
c_{0,3} \cdot \Delta \lambda_p^3 + c_{0,2} \cdot \Delta \lambda_p^2 + c_{0,1} \cdot \Delta \lambda_p + c_{0,0}
\end{cases}, \quad (8)
\]

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

Let us define requirements for the measuring system and the 2\( \lambda \)-FBG profile, which will allow using the 2\( \lambda \)-FBG structure (or an array of 2\( \lambda \)-FBG structures) as sensitive elements of the measuring system.
First, it is necessary to ensure the possibility of polling the characteristic features of the $2\lambda$-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 $2\lambda$-FBG structure falls into the study area.

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 $2\lambda$-FBG 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. Thus, both method requirements are fulfilled.

8. Conclusion

The proposed measuring system is based on the theory and technology of address 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 $2\lambda$-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.

9. References

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