Modelling and record technologies of address fiber Bragg structures based on gratings with two symmetrical pi-phase shifts

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Abstract. Address fiber Bragg structures (AFBS) make it possible to effectively solve the problems of interrogation and multiplexing of sensors in multi-sensor networks with microwave photonic processing of information. Based on a complex method of transmission matrices and the coupling of directional modes, a mathematical model was constructed to determine the spectral profile of a fiber Bragg grating with two discrete symmetric phase π shifts (2π-FBG). Based on the study of the mathematical model, the possibility of selecting the necessary parameters of 2π-FBG AFBS is shown, which allow forming its spectral profile in such a way that the specified structure can be used as a sensitive element of the sensor and provides the necessary linear displacement in the optical range and preserves the required frequency separation – address – between discrete symmetric phase shifts location in the radio frequency range. The analysis of the formation and recording methods for 2π-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 of the fiber were chosen. Further paper deals with issues of interrogation of the developed structures in few- and multi-sensor implementations.

1. Introduction
Recent papers [1-3] have shown that photonic sensors based on fiber Bragg gratings (FBG) are of particular interest for new fields of measurements, since these sensors have low rigidity, long lifespan, compact size, light weight and do not need complex power supply, while providing high measurement resolution and fast data transmission. However, despite the high amount of research work, a number of disadvantages still persist, the main of them is the high cost of optical interrogator.

A conventional FBG is a distributed Bragg reflector, i.e. it is a modified optical fiber with periodic variation in the refractive index of the fiber core. The reflected wavelength $\lambda_B$, also known as the Bragg wavelength, is defined by the following relationship: $\lambda_B = 2n_{eff}A$, where $n_{eff}$ is the effective refractive index of the grating, and $A$ is the grating period. $\Lambda$ and, consequently, the reflected wavelength deviate if the fiber is compressed or stretched, and if the temperature is changed, which makes it possible to use FBGs as sensing elements for measurement of various physical quantities.
In general, the FBGs in fiber-optic sensor systems are multiplexed by means of wavelength-division multiplexing methods [1-3]. In such systems, the sensors are distributed uniformly in the wide wavelength range, and their spectra do not overlap. In the modern photonic systems, the multiplexing of FBG-sensors is fulfilled using optoelectronic interrogators, which consist of broadband light sources for sensors probing and different dispersive or scanning elements for the sensor interrogation. The complexity and high cost of these devices eliminate the wide usage of fiber-optic sensor systems in various industrial applications.

In search of a solution to this problem, the authors paid attention to the spectral-coded FBGs [4-10] and FBGs with two \( \pi \)-phase shifts [11-14].

Spectral-coded FBGs allow a complete separation of responses from few sensors operating on the same central wavelength [4-7]. Spectral-coded sensors are based on code multiplexing technology [6-7]. In particular, optical orthogonal codes are used to form the FBGs spectral structure unique to each sensor. The interrogation of the spectral-coded FBGs is performed in real time by determining an autocorrelation function between the spectrum reflected from the sensor and its code signature. The detection and tracking of sensors for efficient measurement of temperature and strain even under overlapping conditions, using Slepian codes based on orthogonal discrete extended spheroidal sequences, were also demonstrated in several papers [8-10]. 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 [11] they were used to integrate and differentiate optical pulses, in the paper [12] to generate a pair of carriers, in the paper [13-14] 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. Such type of sensor greatly gains in value from all existing ones, if we make them addressable. 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.

Thus, in order to solve the abovementioned interrogation problems, an alternative method for the FBG sensors interrogation was proposed. The main distinctive feature of new microwave photonic sensor system (MWPSS) is the usage of addressed fiber Bragg structures (AFBS) with common central wavelength and two symmetrical \( \pi \)-phase shifts as the temperature or strain sensors, and the frequency spacing between the \( \pi \)-phase shifts is used as a unique identifier (address) of the AFBS.

Further article is constructed as follows. In the second part, the problems of AFBS with two symmetric \( \pi \)-phase shifts 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 fourth and fifth parts deal with issues of interrogation of the developed structures in low- and multi-touch MWPSS implementations.

2. Modelling 2\( \pi \)-FBG AFBS and forming sensors based on them

There are several common methods for modeling the characteristics of 2\( \pi \)-FBGs, among them are the methods of coupled modes, Jones matrices, and the transmission matrix method. The method of coupled modes is often used to describe the synthesis of homogeneous 2\( \pi \)-FBGs due to its simplicity. Matrix methods are used in cases where the grating has a heterogeneous structure. In particular, for modeling the characteristics of 2\( \pi \)-FBG structures, the method based on the construction of the gear matrix was well established. According to the method of 2\( \pi \)-FBG transmission matrices, the structure is divided into \( M \) homogeneous sections (for FBG with two phase \( \pi \) shifts \( 1 < m < M, M = 5 \)), for which the reflection and transmission coefficients of the amplitudes of the modes propagating in the directional and opposite directions are defined after passing of each \( m \) section. The structure of 2\( \pi \)-FBG can be represented as a set of three homogeneous fiber Bragg gratings, arranged one after the other, as shown in figure 1a.
Figure 1. Structure of AFBS with $2\pi$-FBG (a), its spectral characteristics of reflection (b), and example of suitable spectral characteristics of propagation (c).

For each of the sections $S_i(\lambda)$, the transfer matrix is described, and a special matrix $S_\varphi$ is introduced to describe the phase shift. Figure 1b presents $2\pi$-FBG spectral characteristics of reflection. By selecting the parameters of $2\pi$-FBG and analyzing the obtained spectrum, it is possible to form any amplitude-frequency profile of the structure that is required in order to use the structures as sensing elements in MWPSS. An example of the suitable profile shape for the $2\pi$-FBG is presented in figure 1c.

The proposing measurement system is based on the addressed fiber Bragg structures (AFBS) that are realized using $2\pi$-FBG. In that case, $2\pi$-FBGs of all sensors have equal bandwidth and the same central wavelength, while their addresses are provided by the unique frequency spacing between the two transparency windows in the AFBS spectrum. In order to use the $2\pi$-FBG structures or their set as sensing elements of measurement systems, the AFBSs and their interrogation system must satisfy the following requirements:

- The possibility to interrogate the AFBS $\pi$-phase shifts in the whole measurement range must be provided. This requirement is satisfied using wide $2\pi$-FBG structure with nearly rectangular profile.
- Only the light response from $\pi$-phase shifts of $2\pi$-FBG must reach the scope of measurement. This is provided by a laser source, the bandwidth of which is equal to the measurement range, or by an optical bandpass filter of the required range.
- The frequency spacing ($\Omega$) between the phase shift components ($\omega_A$ and $\omega_B$) of AFBS two-frequency response must be much smaller than the optical carrier frequencies, and it must be located in the range of radio spectrum of frequencies: $\Omega << \omega_A$, $\omega_B$.
- The full width at half maximum of the spectral components that make up two-frequency response must be the same and equal to $\delta$, and the absolute value of the width must be much smaller than the frequency spacing: $\delta << \Omega$. 
• A linear inclined filter with the pre-defined characteristics must be placed before the photodetector.

2π-FBG AFBS is relatively easy to produce and can be manufactured using phase mask with minimal requirements for modulation coefficient parameters and uniformity of its profile characteristics. The address of such structure is provided by the fact that the frequency spacing between the two π-phase shifts does not change if strain or temperature field is applied to the 2π-FBG.

3. 2π-FBG AFBS record technology

The analysis of the formation and recording methods for 2π-FBG AFBS was carried out [15-20].

For their manufacture, a specially designed phase mask can be used, which already includes the required phase shifts with the appropriate restrictions on the amplitude, position and number of phase shifts. Another method for recording FBGs is to “inject” a phase shift between two regions of the grating [15]. This method requires a device capable of high-precision fiber or phase mask shifting. Other methods, such as additional ultraviolet irradiation [16] and local heat treatment [17], do not have sufficient accuracy to produce 2π-FBG with specified parameters.

In [18-19], similar to the idea of equivalent chirping, the idea of an equivalent phase shift was proposed, and the desired phase shift in one AFBS is achieved by simply changing the sampling period.

The method of forming 2π-FBGs by recording several Bragg gratings was chosen. The essence of the method is as follows. In optical fiber using conventional interferometric recording schemes (based on the Lloyd or Talbott interferometers) FBG is recorded, then using a precision positioner, the fiber is displaced perpendicularly to the recorded beam and the second FBG is recorded, and so on. The magnitude of the shift and the size of the beam (the length of the FBG) are chosen in such a way that they overlap – a phase shift is formed. For a more accurate control of the magnitude of the bias in the scheme, a Michelson interferometer on bulk optical elements is used [20]. Compared to point-to-point recording, this installation requires only one precision positioner – for fiber pulling (positioning accuracy is ± 5-10 nm), which makes it structurally simpler and cheaper. In addition, the formed 2π-FBGs have a natural apodization of the profile (due to the fact that the recording beam has a Gaussian intensity distribution over its cross section), which reduces the level of lateral maxima (compared to a uniform FBG that does not have apodization).

Obviously, using this method it is possible to form 2π-FBGs with several phase shifts. In our case, it is required to record three FBGs to form two dips in the spectral characteristic. The length of 2π-FBG can be corrected by a set of diaphragms (to reduce the beam - the length of the FBG) or specialized optical circuits (to increase them) [20].

We have demonstrated the possibility of recording FBG with a phase shifts using this technique for different applications [21-25] 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.

4. Interrogation system for two 2π-FBG AFBS

Figure 2 presents the block diagram of the interrogation system for two AFBSs with different address frequencies ω1 and ω2, one of which is used to measure tire strain, and the second one takes into account temperature variation [26].

A broadband light source 1 generates continuous light radiation (diagram a), which corresponds to the measurement bandwidth. The light is transmitted through the optical coupler 9 enters the two AFBSs 2.1 and 2.2. Both AFBSs transmit two-frequency radiation that are summed into a combined radiation (diagram b) using another coupler 10. In the output of the coupler, a four-frequency radiation (diagram c) is formed, which is sent through a fiber-optic splitter 6. The splitter divides the optical signal into two channels – the measuring channel and the reference channel. In the measuring channel, a linear inclined filter 3 is installed that modifies the amplitudes of the four-frequency radiation into the asymmetrical radiation (diagram d). After that, the signal is sent to the photodetector 4 and is received by the measuring ADC. The signal from the ADC is used to define the measurement information from the
AFBS. In the reference channel, the signal (diagram e) is sent to the reference photodetector 7 for the optical power output control, and then it is received by the reference ADC 8. Thus, the normalization of output signal intensity is achieved, and all subsequent calculations are performed using the relations of the intensities in the measuring and reference channels.

**Figure 2.** Block diagram of the interrogation system for two AFBS.

Assume that $\Omega_1 > \Omega_2$, then the total optical response of the two AFBSs can be defined as:

$$F(t) = \left( A_1 \sin(\omega_1 \cdot t) + B_1 \sin((\omega_1 + \Omega_1) \cdot t) \right)^2,$$

where $A_1, B_1$ are the components’ amplitudes of the first AFBS; $A_2, B_2$ are the components’ amplitudes of the second AFBS; $\omega_1, \omega_2$ are the frequencies of the left components from the first and second AFBSs, respectively; $\Omega_1, \Omega_2$ are the address frequencies of the first and second AFBSs, respectively.

The luminous power received by the photodetector can be described by the following expression:

$$P(t) = \left[ A_1^2 + B_1^2 + A_2^2 + B_2^2 \right] + \left[ A_1 B_1 \cos(\Omega_1 t) + A_2 B_2 \cos(\Omega_2 t) \right] +$$

$$\left[ A_1 A_2 \cos(\omega_1 - \omega_2) t + A_1 B_2 \cos(\omega_1 - \omega_2 - \Omega_2) t + B_1 A_2 \cos(\omega_1 - \omega_2 + \Omega_1) t + B_1 B_2 \cos(\omega_1 - \omega_2 + \Omega_1 - \Omega_2) t \right].$$

The oscillations of luminous flux on the photodetector (which are proportional to the output electric power of the photodetector) are used to explicitly define the location of address frequencies of both AFBSs, except for the twelve particular cases, when the frequencies in any of the four components of the third sum (underlined in (2)) coincide with the address frequencies $\Omega_1$, or $\Omega_2$. In order to determine the presence of third component contribution in (2) and the value of this component, additional filters can be installed.

The microwave-photonic sensor system analyzes continuous optical response from the AFBSs, and its interrogation speed can be increased up to hundreds of MHz and resolution – to several Hz, which is defined by the parameters of an electronic (not optical) vector or scalar analyzer of the MWPSS output signal.
5. Multi-sensor network mathematical model and equation system

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.

The form of the spectral response of the signal passing to the measuring photodetector is shown in figure 3, where the following notation is used: \( \omega_i \) – the positions of the left and \( \omega_i + \Omega_i \) the position of the right components; \( \omega_{Br} \) – central (Bragg) frequency; \( \Omega_i \) – the address frequency of AFBS; the amplitudes of the left and right harmonics forming the address frequency are denoted by \( A_i \) and \( B_i \). Difference frequencies \( \Omega_i \) of the sensors which combined in an array do not match each other.

![Figure 3. Shape of the spectral response of the signal applied to the photodetector.](image)

On the photodetector, as on a nonlinear quadratic element, appears all pairing beats \( A_i \) and \( B_i \) of all frequency components. The resulting complex signal is received by an analog-to-digital converter and it serves as a source of information for determination of the central wavelengths of all the sensors in the measurement system.

The total response of the AFBS array at the photodetector is equal to the square of the sum of the responses of all frequency components included in the signal:

\[
F(t) = \left[ \sum_{i=1}^{N} A_i \sin(\omega_i t) + B_i \sin((\omega_i + \Omega_i) t) \right]^2.
\]
The record of the output signal in (3) allows performing transformations that exclude from (3) all the optical high-frequency terms and convert the analysis of the signal into the microwave frequency range. We divide the expression (3) into two separate sums, put the constant factor out of the sum brackets, square the expression, eliminate the multiplier degree, following the procedure for decreasing the degree, and obtain the intermediate expression for the full waveform. Since the photodetector is not sensitive to power fluctuations at optical frequencies, it is possible to exclude all terms from the intermediate expression with oscillations at frequencies higher than the maximum address frequency of the AFBS for the full waveform without losing the physical meaning. The resulting signal after the photodetector on the ADC will be (4):

\[
P(t) = \sum_{j=1}^{N} \sum_{k=1}^{N} \left( A_{Ak} \cos((\omega_k - \omega_j)t) + A_{Bk} \cos((\omega_k - \omega_j - \Omega_k)t) + B_{Ak} \cos((\omega_k - \omega_j + \Omega_k)t) + B_{Bk} \cos((\omega_k - \omega_j + \Omega_k - \Omega_k)t) \right) .
\]

Narrowband filtering of the signal (4) at the address frequencies of AFBS sensors allows to obtain a system of equations (5), which makes it possible to determine the position of the central (Bragg) frequencies of all of the AFBS in the array:

\[
\sum_{j=1}^{N} \sum_{k=1}^{N} \left( \frac{(\omega_j - \omega_k - \Omega_k)^2}{2\sigma^2} + \frac{(\omega_j - \omega_k + \Omega_k)^2}{2\sigma^2} + \frac{(\omega_j - \omega_k)^2}{2\sigma^2} + \frac{(\omega_j - \omega_k + \Omega_k - \Omega_k)^2}{2\sigma^2} \right) = D_j, \quad j = 1, N ,
\]

where \( D_j \) is the amplitude of the signal at the frequency \( \Omega_k \), 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 (5) 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-Raffson method or the Levenberg-Marquardt method, which have quadratic convergence.

The unknown quantities in the system of equations (5) are \( \omega_j \). Amplitudes \( A_j \) and \( B_j \) are connected with \( \omega_j \) through the known parameters of the oblique filter (6):

\[
A_j = L(\omega_j) = u\omega_j + v , \quad B_j = L(\omega_j + \Omega_j) = u(\omega_j + \Omega_j) + v .
\]

All iterative methods involve setting the initial conditions for starting and ensuring the convergence of the iterative process. To ensure the convergence of the method, the data obtained as a solution to the system of equations (5) in the absence of contribution of the cross-beats can be taken as the initial conditions. In this case, the system of equations (5) becomes a set of equations independent from each other, each of which can be solved as a quadratic equation:

\[
\omega^{(0)}_j = \frac{1}{2u} \left[ \sqrt{u^2\Omega_j^2 + 4D_j^u} - (u\Omega_j + 2v) \right] .
\]
It can be shown that (7) is a necessary and sufficient condition for the convergence of the iteration method for solving the system of equations (5).

6. Conclusion
The results of modelling and application of record technologies of address fiber Bragg structures based on gratings with two symmetrical π-phase shifts are presented. The proposed concept of the microwave-photonic sensor system on the base of this type sensor eliminate the disadvantages of the existing solutions, namely: it enables the usage of a less complicated and cheaper interrogation system, while providing the simplicity of the wireless measurement signal transmission, since it inherently lies in the radio spectrum. Examples of the measurement system in few- and multisensory variants are analyzed.

7. References
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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.