Radiofrequency interrogation method in fiber optic nondestructive monitoring systems

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Abstract. This paper discusses the radio-frequency method of interrogation of FBG, its properties, operating principles, and distinctive features. The aim of the work is the consideration and application of FBG interrogation by the radio frequency method. During the work, a theoretical study was conducted, as well as practical modeling of this method. Particular attention is paid to the consideration of fiber-optic sensors and interrogators. Their classification was presented. It describes in detail the various interrogators that are most suitable for the considered method of interrogation. As a result of the work, the dependence of the effect of temperature on the grating shift was revealed.

1. Introduction
Today, the most promising in the field of sensor technologies are fiber optic sensors (FOS) based on Bragg gratings. The radio frequency interrogation technologies of the Bragg gratings at the moment remain a key element in the implementation of the new era of measuring systems. In various field conditions and laboratories, they have been studied for several decades.

Fiber optic sensors have several advantages, such as low weight, small size, resistance to electromagnetic interference, ease of multiplexing, as well as communications. The basis of temperature measurement, deformations from mechanical effects, are sensors based on fiber Bragg gratings (FBG). Also at the heart of the FOS is the change in the refractive index, as well as many other values applicable to the listed ones.

Fiber optic sensors based on a fiber Bragg grating are a device with a "measured value-wavelength" coding. Water, as a rule, turns into a measurable measure the displacement of the central wavelength of its spectral response, or of a certain spectral feature in it.

2. Interrogation
Interrogators are usually made on the basis of optical spectrum analyzers (OSA) or optical filters. Optical filters include a combined spatial filter (CSF), which is based on a diffraction grating and a CCD camera, a Fabry-Perot scanning filter (FPSF), and an optical narrowband filter (ONF), which has a dependence on the wavelength of the spectral characteristic slope.

Among the methods of interrogation of the filter CSF and ONF are considered direct frequency, information on the change in the position of the wavelength in these two methods can be obtained directly.
If you apply the CSF, the wavelength shift will change in advance into a spatial one, and after that it will be determined by the number of the most exposed pixel. The shift of the wavelength in the application of the ONF is converted in advance into a change in power. This change in power depends on the position on the slope of the FBG central filter length. The use of these methods are indirect amplitude and conditionally implement the transformation "wavelength - amplitude - measured quantity".

The radiofrequency method for studying the corrosion of metals under adsorption electrolyte films is considered. Since an oscillating quartz plate has the ability to change its resonant frequency when applied to it of an extraneous mass, it was the basis of the method under consideration.

After analyzing, one can notice that with an increase in the number of gratings, the total reflection coefficient increases, and the envelope spectrum expands. The Bragg structure takes the form of a single fiber Bragg grating when the three first grates in a sequence wear out and the number of gratings decreases.

Important note: only cases of complete wear of the fiber Bragg grating are considered, taking into account the same temperature shifts, including when the total length of one fiber grating is changed, that is, in the case of its partial wear.

The method of determining the number of fiber Bragg gratings was synthesized by the analysis shown in Figure 1. Analysis of the gratings in the sequence, and, accordingly, the level of brush erasure, which is based on finding the quality factor of the common contour for the spectral envelope of sequentially installed fiber Bragg gratings.

Determine the bandwidth of the sequence, depending on the number of arrays, you can determine the position of the center frequency of the two-frequency radiation relative to the center frequency of the array.

The difference-frequency variation method based on the ratio [2] can be expressed as:

\[ Q_{1,2} = \frac{v_{FBRG}}{f_1 - f_2} \sqrt{\frac{\text{out}_{(v_{FBRG})}}{\text{out}_{1,2}}} - 1, \]  
\[ Q_{3,4} = \frac{v_{FBRG}}{f_3 - f_4} \sqrt{\frac{\text{out}_{(v_{FBRG})}}{\text{out}_{3,4}}} - 1, \]  

(1)  
(2)

Since \( Q_{1,2} = 3, 4 \), using the joint solution of equations (1) and (2), we obtain \( \text{out}_{(v_{FBRG})} \). After that, the maximum value of the spectral envelope can be obtained by substituting this value in any of the expressions. Based on this, the amount or amount of wear of the fiber Bragg grating will be determined.

You may notice that the number of gratings in the sequence decreases with a higher reflection coefficient, but as a result, the problem is solved more informatively. The FBG characteristics have various types: phase \( \pi \)-shift, classical with Gaussian form, in the structure of the Fabry–Perot interferometer based on two fiber Bragg gratings with their partial erasure.

According to the proposed method of variation of the difference frequency with partial wear of the fiber Bragg grating, information can be used to analyze the sequence of such gratings. According to the amplitude characteristics of the laser radiation reflected from the array of gratings, a measurement of the amount of wear can be carried out. Also, the measurement of the amount of wear can be determined by the general spectral characteristic, for which it will be necessary to determine the expansion of the spectrum at an established, fixed level.

Measurement of the error value of the low-order ADC in the registration system will be determined in the first case. Determining the magnitude of the error of the interrogator - in the second. Measurement of wear in tenths of a micron is possible in both cases.

Improving the reliability and accuracy of measuring the density of an electrolyte when the ambient temperature changes from \(-60 \) to \(+60 \) °C is one of the specific tasks of research in the field of battery operation. It is not unimportant to develop a method to automate the measurement process, as well as to maximally simplify the design of the device as part of a diagnostic system. As an example, lead
batteries can be given to ensure continuous monitoring of the density of the electrolyte during the entire period of their work based on fiber-optic sensors.

![Figure 1. Reflection envelope spectra.](image)

One of the most important parameters that tell us about the failure of lithium-ion batteries is the temperature. But the control of temperature distribution throughout the battery is present even in the most advanced battery management systems. Changing the size (volume) of the battery can indicate an additional parameter of the temperature profile. The considered parameters, as well as the index of refraction (IR), can be simultaneously monitored using fiber-optic sensors to monitor the operating parameters of a battery consisting of several fiber Bragg gratings with phase $\phi$-shift. In the previously reviewed papers, a solution was proposed for the simultaneous measurement of IR and temperature.

### 3. Interferometry with the frequency shift

Frequency shift interferometry (FSI) allows you to extract information from the transmitted signal on the reflection coefficient of several, even spectrally overlapping gratings, as well as location. The FSI method, unlike other methods, relies on Sagnac interference.

There is a phase difference between the two components of the probing radiation, which traveled the same path in the fiber and have the same frequency, shifted relative to the carrier radiation, but received this shift at different points in their path. From the relationship between the phase change and
the component shift in frequency, the position of the sensor can be determined. The FSI method differs from the OFDR value. This allows you to extract information from a powerful low-coherent radiation source. The use of a source of continuous radiation, as well as the non-necessity of using a photodetector with high speed, gives FSI an advantage over TDM. When compared with WDM, it is possible to interrogate several sensors, even if their spectra are overlapped. Acoustic optical modulators (AOMs) were used in various FSI schemes to obtain data on the shear frequency in the Sagnac interferometric circuit.

Dual-frequency, or polyharmonic, radiation was not previously used in the interferometric method FSI. The advantages of its use in the formation of an optical carrier conversion according to the amplitude-phase method of the Ilyin-Morozov force is that the capabilities of the carrier frequency depend on the constant component of the interference signal. When sampling each of the components using filters, it allows FSI at the same reflectance of the sensor in the entire frequency band. The formation of polyharmonic radiation based on a combinatorial generator will allow you to create a broadband low-coherent source, which, in sum, with the above changes, reduces the amount of crosstalk between sensors. As a result, this will increase the resolution, increase the effect of the signal - the measurement range, as well as noise. It is necessary to comply with the requirements of universality and uniform polarity in such an implementation.

There is the possibility of using a single laser emitter and the formation of a combinatorial generator for several measurements of channels. To separate them, you can apply an ordered wave array and a separate photodetector on each of its channels.

The dual-frequency method of probing both the external Gaussian reflection contour and its central Lorentz transmission contour was used in this method.

For each of the circuits, signal processing was carried out for the envelopes at certain intermediate frequencies. When this occurs, the formation of a two-loop measurement system with a "rough" Gaussian and "exact" Lorentz contours. In Figure 2 shows the structure of an integrated sensor for measuring refractive index and temperature.

![Figure 2. Sketch of the structural scheme of a FOS of a parallel structure of two gratings: from above — a fiber with an etched FBG2 shell of the refractive index bottom - fiber with a whole shell FBG1 temperature.](image)

When applying physical interaction to the region of the intersection point of the sensor axis and the center of the FBG, induced chirping of the grating appears $\Delta \lambda_{chirp}$: the lower part is stretched, the upper part is compressed.

On this basis, an increase in the width of the grating will be defined as:

$$\Delta \lambda_{chirp} = \frac{\lambda_{FBG} k (1-P_e) \sin(2\theta)}{2},$$

where $k$ is the coefficient of bending FBG (1/m); $P_e$ – fiber photoelasticity coefficient.

If you need to use complex spectral instruments to measure the lattice width, then you can use the four-frequency sounding technique with two unequal difference frequencies, without changing the frequency of the laser, to measure the dip width.

Figure 3 shows the use of a FBG-based fiber optic sensor with phase $\pi$-shift for various applications.
Figure 3. Fiber optic sensor based on a fiber Bragg grating with phase $\pi$-shift, inclined to the axis of application of the impact (a, b) and the width of the transparency window in microns (c) before (A) and after (B) bending.

In the study of FBG with a phase $\pi$-shift, it was also noted that with temperature changes the structure of lattices of this type remains unchanged.

The FBG transparency window, caused by the phase $\pi$-shift, is broadened with preservation of the gradient of the steepness of the general broadening of the FBG, this was shown by the research method. The width of the dip was 0.01 nm, with no impact.

In the end, we get, if you need to use complex spectral instruments to measure the lattice width, then you can use the four-frequency sounding technique with two unequal difference frequencies, without tuning the laser frequency, to measure the dip width.

Difference frequencies for operation should be in the range of 100–300 MHz based on the width of the dip. The process of finding the resonance wavelength of the FBG, its width and the height of the lattice at half-height, which was considered earlier, received the name “difference frequency variation method”.

Figure 4 shows the dependence of the change in the width of the failure of the fiber Bragg grating with the phase $\pi$-shift from the effect inducing chirping (Figure 4 (a) and temperature (Figure 4 (b)).
Figure 4. Dependences of the change in the width of the failure of the fiber Bragg grating with the phase $\pi$-shift from the curvature coefficient (a) and temperature (b).

The sensor is placed obliquely to the axis of application of the tensile force, the magnitude of which is determined by the dynamics of the lattice dip width at half-height in the $\pi$-shift zone. The gradient of lattice width variation is identical to the gradient of dip width variation, and can be registered using low-mode sounding methods with a simple hardware implementation due to its smallness. The results of the research obtained in an experimental study at the KNRTU-KAI fully confirmed the developed theoretical principles.

4. Conclusion
In this paper, from the standpoint of generalization of the results of development and practical application, the classification of fiber optic sensor interrogators based on fiber Bragg gratings based on optical-electronic and radiophoton technologies using frequency and amplitude measurement wavelength conversion technologies is presented.

The results of the development are summarized and proposed as a separate class - the class of radiophoton interrogators with amplitude-phase measurement conversion. The use of such interrogators will increase the resolution of interrogation to hundredths of pm and increase the polling rate to 10-50 MHz.

Examples of the development of interrogators of the specified class are presented, providing a complex measurement of several, at least two simultaneously acting physical quantities on a FOS. Simultaneously with the temperature measurement, the wear of the friction surface is measured (for example, an electric motor brush), the refractive index of the substance into which the sensor is immersed (for example, measuring the octane number of gasolines), the transverse pressure or the slope of the sensor bending (for example, the sensor for overcoming the optical fiber perimeter protection barriers). It is shown that with appropriate software processing, measurement of values with an error in fractions of a percent can be achieved.

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”).

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