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Fiber optic gyroscope with output signal noise reduction system: effect of system parameters on noise reduction

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Abstract. The *purpose* of this work is to determine the optimal parameters for matching the signals of the measuring channels of a fiber-optic gyroscope with an output signal noise reduction system. *Methods.* The paper analyzes the circuit of a fiber-optic gyroscope with an output signal noise reduction system based on subtracting the signal of the reference measuring channel containing the intensity noise of the optical radiation source from the signal of the main measuring channel containing the useful information signal and the noise component. Four signal matching conditions are defined, failure to meet which can lead to a decrease in the noise suppression efficiency or an increase in the noise level. For each of the conditions under consideration, the parameters of the noise reduction system are determined and mathematical expressions are derived for the dependence of their influence on the level of spectral density of noise in the output signal of the gyroscope, mathematical modeling is carried out in a wide range of variation of the parameters under consideration. To confirm the obtained results, a computer simulation of the operation of a digital fiber-optic gyroscope with a closed feedback loop for measuring angular velocity and an output signal noise reduction system was carried out under conditions of varying the parameters of the noise reduction system. *Results.* For each parameter under consideration, the shape and degree of influence on the noise level were obtained, and the optimal value of each parameter was determined, at which the minimum value of the spectral density of noise in the output signal was observed. *Conclusion.* The conducted study confirms the correctness of the derivation of analytical expressions describing the formation of the noise component of the output signal of a fiber-optic gyroscope with a noise reduction system under conditions of incomplete matching of the signals of the main and reference measuring channels. A quantitative assessment of the requirements for the accuracy of this matching was obtained for such parameters as: time matching, matching by signal intensity, by bandwidth and by the state of polarization of optical radiation.

Keywords: fiber optic gyroscope, output noise of fiber optic gyroscope, noise compensation, noise suppression, mathematical model, correlation.

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Introduction

At the current level of technological development, fiber-optic gyroscopes are one of the most fundamental and promising types of angular rate sensors used in orientation, navigation, and stabilization systems for moving objects, in terms of further improving their accuracy [1–3]. Reducing the noise component in the fiber-optic gyroscope's output signal is a priority for improving the accuracy of the products in which they are used.

The sensitivity threshold of a fiber optic gyroscope and the long-term stability of the zero signal of a fiber optic gyroscope largely depend on its design characteristics — the length and diameter of the Sagnac interferometer fiber loop, the type of fiber laying in the loop, etc., as well as the properties of the optical elements of the circuit: the width of the spectrum of the radiation source, the absence of internal defects, a low level of h — the fiber parameter [4] — and the quality of the electronic element base — the intrinsic noise of operational amplifiers, analog-to-digital converters, etc. The most optimal in terms of the combination of these parameters at the current level of technology are fiber optic gyroscopes with a loop length of 1000...2000 m and a fiber loop diameter of 100...150 mm, wound using the quadrupole method from polarization-maintaining fiber, with a broadband optical radiation source: a superluminescent diode or an erbium superluminescent fiber source of high output power. An analysis of technical documentation for commercially available fiber optic gyroscopes shows that, depending on the parameters and features listed above, as well as the use of non-standard design, circuitry, or algorithmic approaches, specific values of parameters such as noise spectral density and random component (long-term stability) of the zero signal are, on average, in the following ranges: noise spectral density — 0.1...0.03 $(^\circ/\mathrm{h})/\sqrt{\mathrm{Hz}}$, random component of the zero signal in the operating temperature range (three standard deviations with an averaging time of 100 s) — 0.06...0.15 °/h.

In [4, 5] the main noise sources in a fiber optic gyroscope were examined and the source making the largest contribution to the resulting noise of the fiber optic gyroscope's output signal was identified. Various methods for reducing the influence of this noise source are presented in [6,7]. In [8,9] the results of mathematical modeling were presented, as well as the results of full-scale tests of a fiber optic gyroscope prototype with a noise reduction system in the output signal. This system is based on subtracting the signal of the reference measuring channel, which contains only the noise component, from the signal of the main measuring channel, which contains both useful information and noise components. It was shown that the use of this method allows for a reduction in the spectral density of the noise of the fiber optic gyroscope's output signal by approximately a factor of two. In absolute terms, the use of this system made it possible to achieve noise spectral density values at the level of 0.02 $(^\circ/\mathrm{h})/\sqrt{\mathrm{Hz}}$, as well as to improve the random component of the zero signal at a constant temperature [9].

This paper identifies the factors that lead to deterioration in noise reduction system performance when parameters are changed. Mathematical expressions are derived that describe the dependence of the spectral noise density of the fiber optic gyroscope output signal on the parameters of the measurement channels. Mathematical modeling was conducted, allowing for quantitative assessments of the impact of various parameters on the efficiency of the noise reduction system.

1. Generalized analytical mathematical expression for the spectral density of the noise component of angular velocity

The fundamental noise sources that make the main contribution to the noise component of the output signal of a fiber-optic gyroscope include: 1 — photocurrent shot noise, 2 — photodiode dark current shot noise, 3 — photodiode load resistance thermal noise, 4 — optical radiation source intensity noise. The spectral densities of the noise current of these sources are described by the expressions (1)–(4) [4,5,10]:

$$i_{n1} = \sqrt{e\eta P_0}, \tag{1}$$

$$i_{n2} = \sqrt{ei_d}, \tag{2}$$

$$i_{n3} = \sqrt{\frac{4kT}{R}}, \tag{3}$$

$$i_{n4} = \sqrt{\frac{\lambda^2}{2K_f c\Delta\lambda}}\eta P_0, \tag{4}$$

where i_n is the noise spectral density defined as the root of the variance in a limited frequency band and the frequency [11,12] reduced to this band, $\mathrm{A}/\sqrt{\mathrm{Hz}}$; e is the electron charge, C; η is the efficiency (current sensitivity) of the photodiode, (0.93 A/W; P_0 is the power of optical radiation incident on the photodiode at zero phase difference of counterpropagating light waves ($88\cdot10^{-6}$ W); i_d is the dark current of the photodiode, ($20\cdot10^{-9}$ A; k is the Boltzmann constant, J/K; T — ambient temperature, (293 K); R — resistance of the current-to-voltage converter resistor, (5000 Ohm); λ — average wavelength of optical radiation, ($1565\cdot10^{-9}$ m); c — speed of light in vacuum, m/s; K_f — shape coefficient of the optical radiation spectrum [13], (2); $\Delta\lambda$ — width of the radiation spectrum, ($35\cdot10^{-9}$ m). The numerical values of the parameters given in brackets and used in further calculations correspond to the values of the parameters in the work [9].

The resulting expression for the noise component of the output signal of a fiber optic gyroscope constructed according to the so-called "minimal configuration" scheme, taking into account (1)–(4), has the form:

$$\delta\omega_n = M\frac{\sqrt{i_{n1}^2\frac{1}{2}(1+\cos\varphi)+i_{n2}^2+i_{n3}^2+i_{n4}^2\frac{1}{4}(1+\cos\varphi)^2}}{\eta\frac{1}{2}P_0\sin\varphi}, \tag{5}$$

where $\delta\omega_n$ is the angular velocity noise spectral density, $(\mathrm{rad/s})/\sqrt{\mathrm{Hz}}$; $M = \dfrac{\sqrt{2}\lambda c}{2\pi DL}$ is the inverse of the optical scale factor of the Sagnac effect, rad/s; D is the diameter of the annular multi-turn fiber loop, (0.135 m); L is the length of the fiber loop, (1070 m); φ is the phase difference of counterpropagating light waves, rad.

The factor in the first and fourth terms of expression (5) describes the dependence of the incident radiation power on the photodiode on the phase difference φ of the counterpropagating light waves in the Sagnac interferometer. The denominator of expression (5) is the sensitivity function of the fiber optic gyroscope's output signal on the optical radiation power P_0 and the phase difference φ of the counterpropagating light waves. Recall that in modern fiber optic gyroscopes with auxiliary phase modulation and a closed feedback loop for measuring angular velocity, φ corresponds to the depth of the auxiliary phase modulation and is typically equal to $\pi/2$.

Численный анализ выражения (5) и отдельных его составляющих, проведенный в работе [10], показывает, что увеличение мощности оптического излучения P_0 в диапазоне от 5 до 50 мкВт приводит к значительному снижению уровня шума выходного сигнала. В то же время дальнейшее уменьшение шума при росте мощности излучения практически отсутствует, так как ограничено вкладом шума интенсивности источника излучения, не зависящего от мощности P_0, в результирующий шум.

A numerical analysis of expression (5) and its individual components, conducted in [10], shows that increasing the optical radiation power P_0 in the range from 5 to 50 W leads to a significant reduction in the output signal noise level. At the same time, further noise reduction with increasing radiation power is virtually nonexistent, as it is limited by the contribution of the radiation source intensity noise, independent of the power P_0, to the resulting noise.

In [8,9] a method for reducing the noise level in the output signal of a fiber optic gyroscope is considered. This method is based on subtracting the intensity noise of the optical radiation source from the useful signal. For this purpose, an additional measuring channel is introduced into the fiber optic

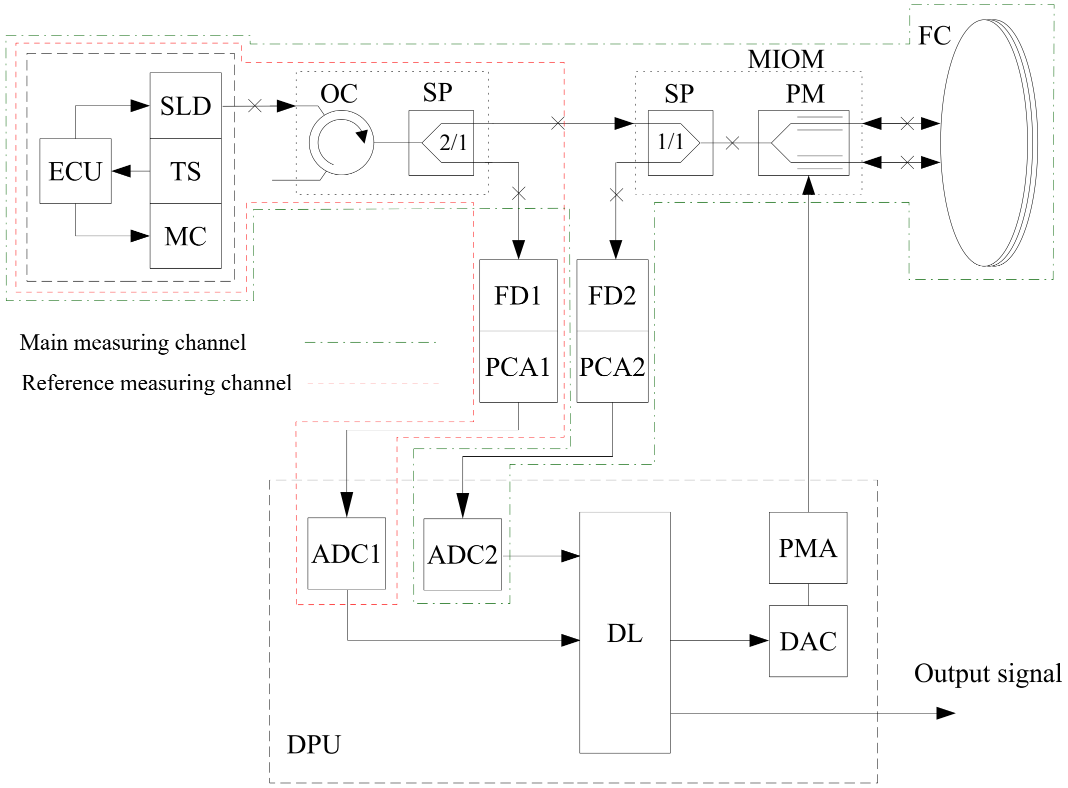

Fig. 1. Block diagram of a FOG with output signal noise reduction system, where ECU is the emitter control unit, SLD is a superluminescent diode, TS is a temperature sensor, MC is a microcooler, OC is an optical circulator, SP is a splitter-polarizer, FD1,2 are photodiodes, PCA1,2 are photocurrent amplifiers, ADC1,2 are analog-to-digital converters, DL is digital logic, MIOM is a multifunctional integrated optical module, PM is a phase modulator, PMA is a phase modulation amplifier, DAC is a digital-to-analog converter, DPU is a digital processing unit, FC is a fiber optic circuit (color online)

gyroscope circuit for measuring the intensity noise of the optical radiation source. The signal measured by this channel, after certain digital processing, is subtracted from the main information signal of the fiber optic gyroscope. Fig.1 shows a functional block diagram of a fiber optic gyroscope with a noise reduction circuit, including the main measuring channel (MC1), implemented according to the Sagnac interferometer circuit, the output signal of which includes both the useful component, containing information about the measured angular velocity, and the noise component, and an additional, reference measuring channel (MC2), the output signal of which contains only the noise component.

As can be seen from Fig. 1, both measuring channels have a common source of optical radiation – a superluminescent diode, which, according to [5, 10], makes the main contribution to the resulting noise of the fiber optic gyroscope output signal (the radiation source noise is described by expression (4)). Each measuring channel also contains its own photodetector, consisting of a photodiode and a photocurrent amplifier, which are sources of statistically independent noise described by expressions (1)–(3).

The expression for the spectral density of the angular velocity noise of the output signal of a fiber optic gyroscope with noise suppression is generally written as follows:

$$\delta\omega_n = M\frac{\sqrt{i_{n1}^2\frac{1}{2}(1+\cos\varphi)+i_{n2}^2+i_{n3}^2+K^2(i_{n1}^2+i_{n2}^2+i_{n3}^2)+\left(i_{n4}^2\frac{1}{4}(1+\cos\varphi)^2+i_{n4}^2K^2\right)(1-K_s)}}{\eta\frac{1}{2}P_0\sin\varphi}, \quad (6)$$

where K is the coefficient that takes into account the need to bring the average signal power of the reference measuring channel to the average power of the main measuring channel; K_s is the intensity noise suppression coefficient.

Let us fix the value of φ equal to $\pi/2$, and take the coefficient K equal to 0.5, then the expression for the spectral density of the noise of the output signal of a fiber optic gyroscope with noise suppression will take a more compact form, convenient for further analysis:

$$\delta\omega_n = M\frac{\sqrt{\frac{1}{2}i_{n1}^2 + i_{n2}^2 + i_{n3}^2 + \frac{1}{4}(i_{n1}^2 + i_{n2}^2 + i_{n3}^2) + \frac{1}{2}i_{n4}^2(1 - K_s)}}{\eta\frac{1}{2}P_0}. \tag{7}$$

2. Conditions for signal consistency of measuring channels

The minimum output signal noise level is achieved when the K_s coefficient is equal to unity, provided that the noise component described by expression (4) in the signals of the primary and reference measurement channels is completely identical. Let us define the meaning and criteria for this "identity."

2.1. Time synchronization. The signals from the measurement channels must be synchronized in time and fed to the unit that subtracts the signal from reference measurement channel 2 from the signal from main measurement channel 1 simultaneously. According to the circuit shown in Fig. 1, the optical signal is split by the polarizer splitter 1 : 2 into two components. One component is fed directly to photodetector-1 (reference measurement channel-2), while the other component passes through the Sagnac interferometer (main measurement channel-1). The distance traveled by the optical signal in measurement channel-2 is approximately one meter. In this case, the propagation time of radiation in an optical waveguide 1 meter long with a refractive index of $n \approx 1.46$ is $4.87 \cdot 10^{-9}$ seconds, in the measuring channel-1 the optical radiation passes through a fiber circuit, the length of which can be from hundreds to thousands of meters, for definiteness we will set a specific length of the fiber circuit equal to 1070 meters (such an "uneven"length is explained by the design features of a fiber optic gyroscope with digital signal processing), while the propagation time of optical radiation in the measuring channel-1 is $5.21 \cdot 10^{-6}$ seconds. Thus, the time mismatch of signals is $\sim 5.21 \cdot 10^{-6}$ seconds.

The dependence of the noise reduction factor K_s on the signal mismatch time Δt can be expressed using the correlation function of these signals. The specific form of the function is determined by the type of noise spectrum and the signal processing algorithm in the fiber optic gyroscope, which results in the original broadband signal being subjected to frequency conversion, which consists of decimation of the signal to a frequency equal to twice the FPM frequency and the transfer of the spectrum's center frequency to zero.

Based on the shape of the signal spectrum and the signal processing algorithm, the band-pass noise correlation function was selected — $\cos(f_0\Delta t)\dfrac{\sin(\Delta f \Delta t/2)}{\Delta f \Delta t/2}$, where f_0 is the central frequency of the spectrum, Δf is the width of the spectrum.

Since the remaining noise sources (except for the intensity noise of the radiation source, described by expression (4)) are initially uncorrelated and their time shift relative to each other does not affect their degree of correlation and their contribution to the resulting noise level, we obtain the following expression for the dependence of the spectral density of the noise of the output signal of the fiber optic gyroscope on the time of mismatch of the signals of the measuring channels:

$$\delta\omega_n(\Delta t) = M\frac{\sqrt{\frac{1}{2}i_{n1}^2 + i_{n2}^2 + i_{n3}^2 + \frac{1}{4}(i_{n1}^2 + i_{n2}^2 + i_{n3}^2) + \frac{1}{2}i_{n4}^2\left(1 - \cos(f_0\Delta t)\frac{\sin(\Delta f \Delta t/2)}{\Delta f \Delta t/2}\right)}}{\eta\frac{1}{2}P_0}, \tag{8}$$

where f_0 is the auxiliary modulation frequency, Hz; Δf is the spectrum width in the system under consideration, proportional to the sampling frequency of the output signal.

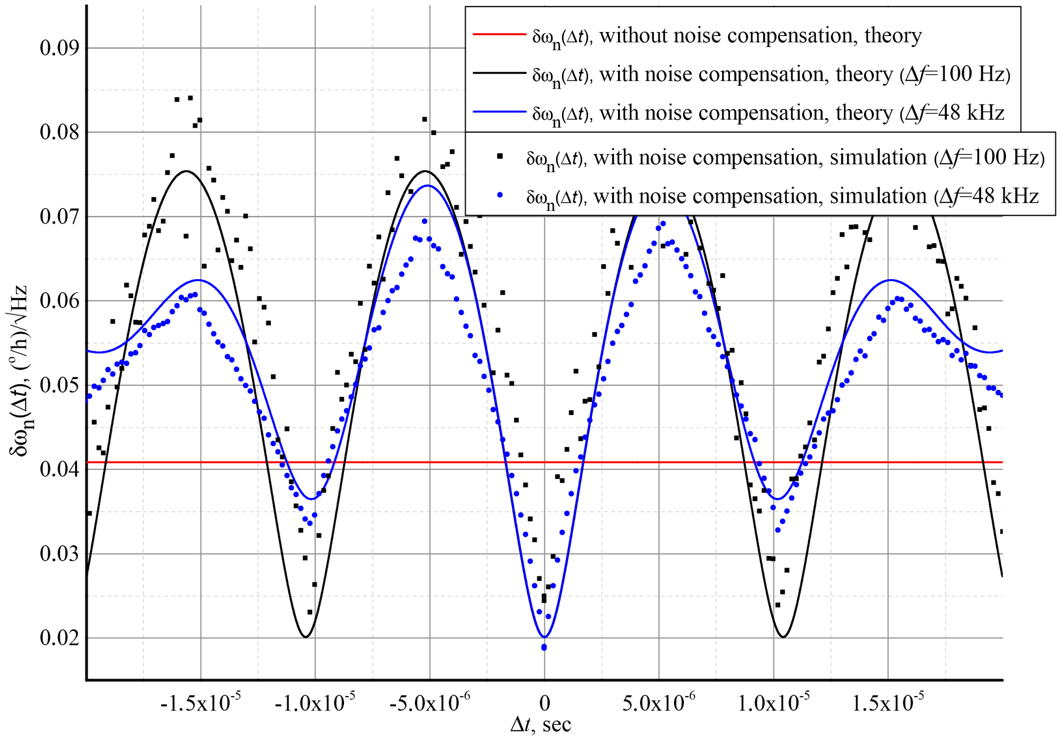

Fig. 2. Dependence of the noise of the output signal of the FOG with noise compensation on the time of signal mismatch at different Δf (black and blue graphs), the noise level of the output signal of the FOG without compensation at the same parameters (red graph) (color online)

Fig. 2 shows the dependence of the noise spectral density on the mismatch (mutual shift) time of the measurement channel signals at different sampling rates of the output signal of a fiber optic gyroscope with a noise reduction circuit.

The solid lines represent the results of calculations using the analytical expression (8), and the dots represent the results of computer simulation. The computer model used for this purpose is described in detail in [9,10]. This model is a computer simulation of a digital fiber optic gyroscope of the compensating type with pulse phase modulation, developed in the "Octave"environment.

На рис. 2 видно, что минимальный уровень шума выходного сигнала достигается в очень узком диапазоне времени рассогласования сигналов измерительных каналов. При этом максимальный уровень шума наблюдается при времени рассогласования порядка 4.5...5.5 мкс (в зависимости от ширины спектра Δf), что соответствует времени задержки распространения оптического излучения в волоконном контуре измерительного канала-1.

Fig. 2 shows that the minimum output signal noise level is achieved within a very narrow range of mismatch times of the measurement channel signals. In this case, the maximum noise level is observed at a mismatch time of the order of 4.5...5.5 s (depending on the spectral width Δf), which corresponds to the propagation delay time of optical radiation in the fiber circuit of measuring channel-1.

2.2. Equality of signal intensity. Let us consider the diagram of measuring channels 1 and 2, shown in Fig. 1. Measuring channel 1 contains a fiber optic loop, the length of which can reach several thousand meters. The optical power loss in the waveguide under normal conditions is approximately 1.5...2.5dB/km. Depending on external factors (temperature, pressure, etc.), the optical power loss in the optical path can vary significantly. This leads to a change in the optical power level arriving at photodiode 2 of measuring channel 1. At the same time, the length of the optical line of measuring channel 2 does not exceed one meter, so the optical power loss caused by the above-mentioned factors can be neglected. To determine the effect of the difference in optical power in the measuring channels on the noise suppression efficiency, we modernize expression (7) by introducing the coefficient K_{OP}. By changing this coefficient

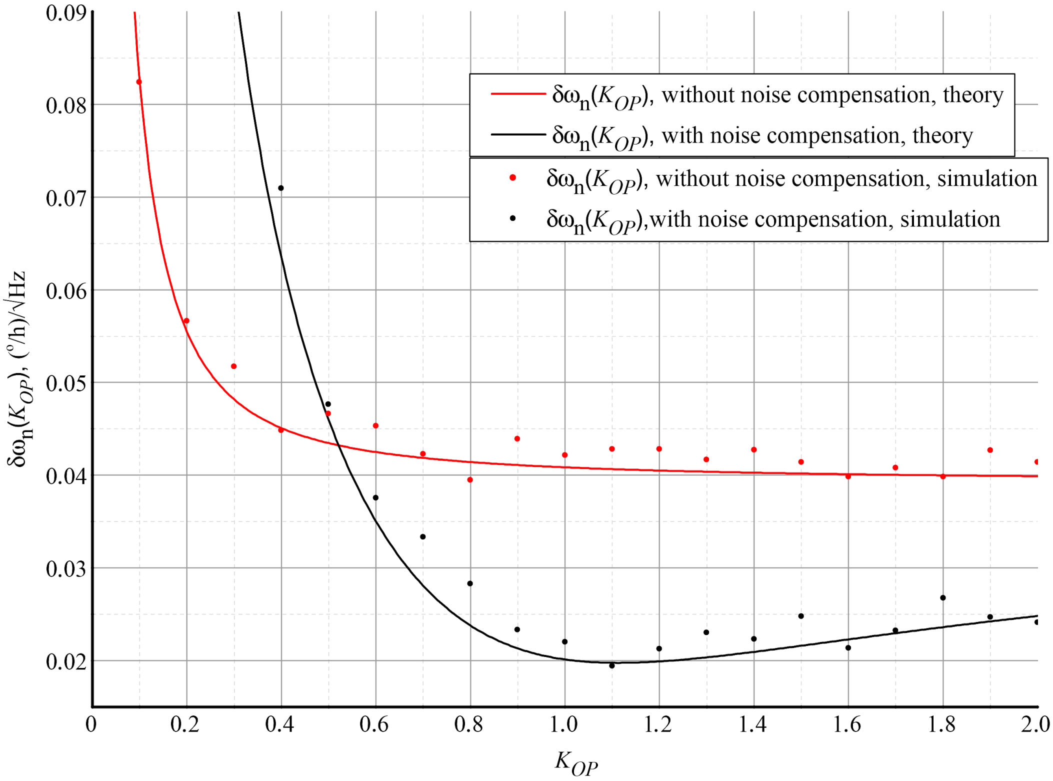

Fig. 3. Dependence of the output signal noise of the FOG with noise compensation and the FOG without noise compensation on the value of the coefficient K_{OP} of the optical emission power in main measuring channel (color online)

K_{OP} we will change the value of the optical radiation power in the main measuring channel.

$$\delta\omega_n(K_{op}) = M\frac{\sqrt{K_{op}\frac{1}{2}i_{n1}^2 + i_{n2}^2 + i_{n3}^2 + \frac{1}{4}(i_{n1}^2 + i_{n2}^2 + i_{n3}^2) + \frac{1}{4}i_{n4}^2(1 - K_{op})^2}}{K_{op}\eta\frac{1}{2}P_0}. \tag{9}$$

Fig. 3 shows graphs of the spectral density of the noise of the output signal of a fiber optic gyroscope as a function of the power factor K_{op} of the optical signal in the main measuring channel. From the graphs of the dependence of $\delta\omega_n$ on K_{op} it is evident that when the optical radiation power level in the measuring channel 1 is lower than in the measuring channel 2 (in the range of K_{op} values from 0 to 1), there is a sharp increase in the noise level of the output signal, caused by two reasons: a decrease in the signal-to-noise ratio in the measuring channel 1 (this can also be seen from the graph of the noise level for the fiber optic gyroscope without noise compensation) and an increase in the output signal of the noise "weight" of the measuring channel 2. When the optical radiation power level in the measuring channel 1 is higher than in the measuring channel 2 (in the range of K_{op} values from 1 to 2), the noise level smoothly increases due to a decrease in the noise suppression coefficient caused by the incomplete subtraction of the correlated noise (the intensity noise of the radiation source) of the measuring channels.

In measuring channel 1 and measuring channel 2, the optical signal is fed to the corresponding photodetector, where it is converted into an electrical signal, which is then fed to an analog-to-digital converter and subsequently digitally processed using the fiber-optic gyroscope operating algorithms. The electrical and digital path of each signal is characterized by its own conversion/amplification/attenuation coefficients, the complex effect of which on the noise level of the output signal is expressed through the

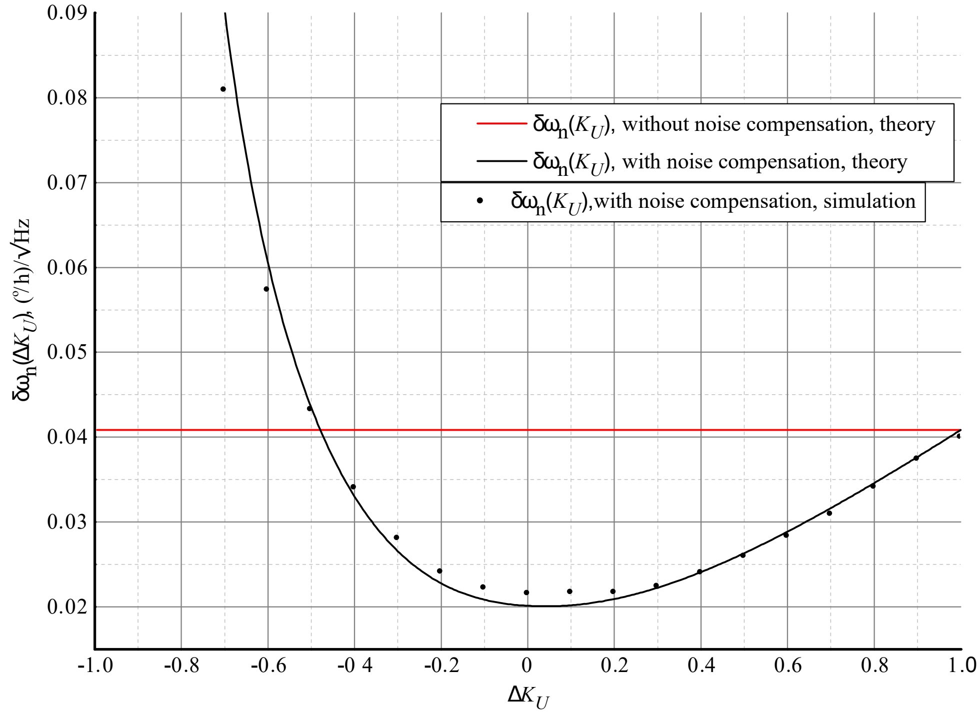

Fig. 4. Dependence of the noise of the output signal of the FOG with noise compensation on ΔK_u — the ratio of the gain factors of the signals of the measuring channels (black graph), the noise level of the output signal of the FOG without compensation with the same parameters (red graph) (color online)

corresponding coefficients K_{u1}, K_{u2} of expression (10):

$$\delta\omega_n(\Delta K_u) = M\frac{\sqrt{K_{u1}^2\left(\frac{1}{2}i_{n1}^2 + i_{n2}^2 + i_{n3}^2\right) + \frac{1}{4}K_{u2}^2(i_{n1}^2 + i_{n2}^2 + i_{n3}^2) + \frac{1}{4}i_{n4}^2\Delta K_u^2}}{K_{u1}\eta\frac{1}{2}P_0}, \tag{10}$$

where K_{u1}, K_{u2} are normalized coefficients (range of values from 0 to 1) of conversion/amplification of signal amplitude in photoconverter devices and digital signal processing paths, $\Delta K_u = K_{u1} - K_{u2}$ is the difference between the normalized coefficients.

Fig. 4 shows graphs of the spectral density of the output signal noise of a fiber optic gyroscope as a function of the difference in the signal gains of the measuring channels ΔK_u. From the graphs of the dependence of $\delta\omega_n$ on ΔK_u, it is evident that as the signal amplitude of reference measuring channel 2 decreases (a decrease in the coefficient K_{u2} in the range of ΔK_u values from 0 to 1), the noise level increases due to a decrease in the noise suppression coefficient caused by the incomplete subtraction of the correlated noise of the measuring channels. As the signal amplitude of main measuring channel 1 decreases (a decrease in the coefficient K_{u1} in the range of ΔK_u values from 0 to -1), the signal-to-noise ratio further deteriorates, which is caused by a relative increase in the resulting signal noise of the signal of measuring channel 2.

2.3. Bandwidth. In [6], it was noted that for the noise reduction circuit to be as effective as possible, the bandwidth of the photodetectors in the main and reference measurement channels must be equal. Let's consider how the noise level in the output signal of a fiber optic gyroscope depends on the ratio of the bandwidths of the photodetectors in the measurement channels. We note the following:

- the bandwidth of the photodetectors and the sampling frequency of the analog-to-digital converter are chosen to be sufficiently large (on the order of tens of megahertz) to accurately reproduce the original signal in digital form for further processing;

- the signal processing algorithm in the fiber optic gyroscope involves averaging the original broadband digitized signal over time intervals equal to $1/(2f_0)$, where f_0 is the frequency of the pulse phase modulation of the signal, which can be approximately considered equivalent to using a first-order low-pass filter with a cutoff frequency of $2f_0$. Depending on the length of the fiber circuit, the frequency f_0 ranges from tens of kilohertz to several megahertz.

Thus, high-frequency components of the signal's noise spectrum are filtered out during digital signal processing using fiber-optic gyroscope algorithms. A noticeable effect of varying photodetector bandwidths will only be observed when narrowing this bandwidth to frequencies of the order of f_0.

Taking into account the uniform spectral density of noise in the bandwidth range of the photodetectors, it is possible to define a normalized function that describes the dependence of the effective bandwidth of the measuring channel on the bandwidth of the photodetector for each measuring channel: $\Delta F_1 = 1 - f_0/\Delta f_1$, $\Delta F_2 = 1 - f_0/\Delta f_2$, where Δf_1, Δf_2 — the bandwidth of the photodetectors of measuring channels 1 and 2, respectively.

To determine the quantitative influence of the difference in the bandwidth of the photodetectors on the level of noise reduction in the output signal of a fiber optic gyroscope, we introduce into expression (7) the above-defined normalized functions of the dependence of the intensity of the noise components of

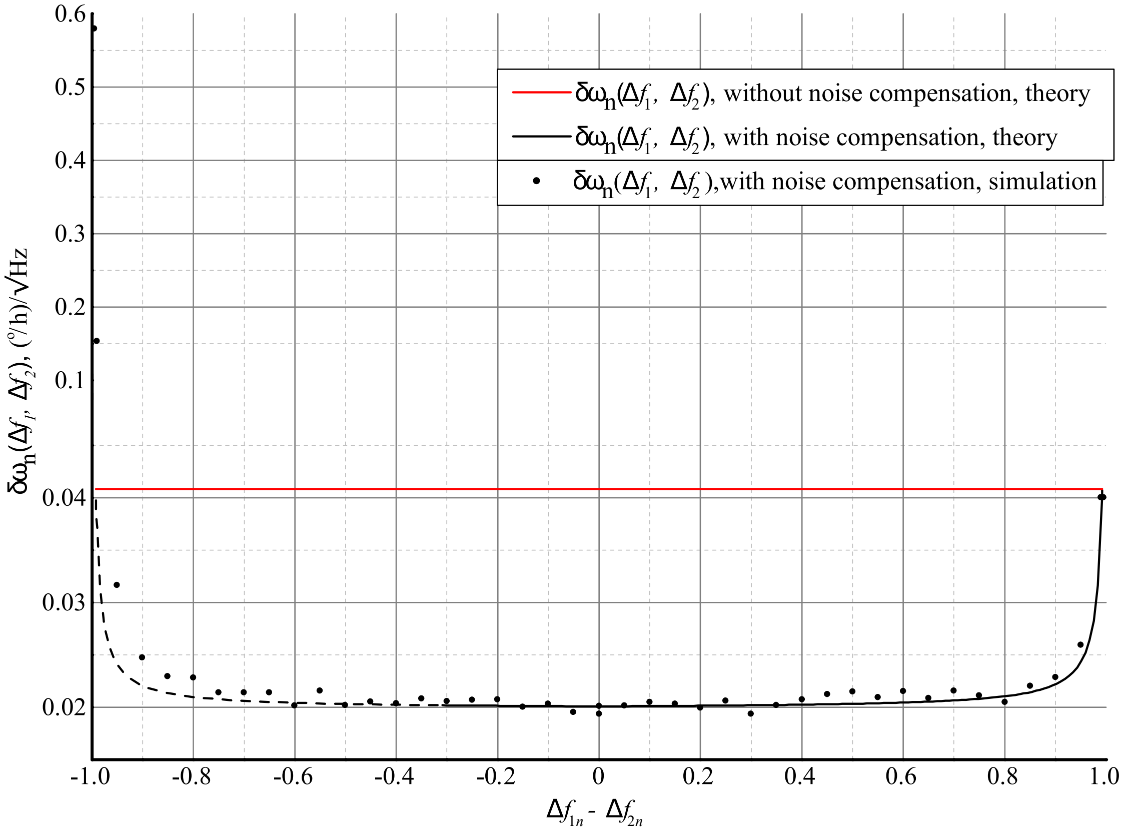

Fig. 5. Dependence of the noise of the output signal of the FOG with noise compensation on the ratio of the normalized bandwidth of the photodetectors (black graph), the noise level of the output signal of the FOG without compensation with the same parameters (red graph) (color online)

the signal on the bandwidth of the photodetectors:

$$\begin{aligned}&\delta\omega_n(\Delta f_1,\Delta f_2) =\\ &= M\frac{\sqrt{\left(1-\dfrac{f_0}{\Delta f_1}\right)\left(\dfrac{1}{2}i_{n1}^2+i_{n2}^2+i_{n3}^2\right)+\dfrac{1}{4}\left(1-\dfrac{f_0}{\Delta f_2}\right)(i_{n1}^2+i_{n2}^2+i_{n3}^2)+\dfrac{1}{4}i_{n4}^2\left|\left(1-\dfrac{f_0}{\Delta f_1}\right)-\left(1-\dfrac{f_0}{\Delta f_2}\right)\right|}}{\eta\dfrac{1}{2}P_0}.\end{aligned} \tag{11}$$

The dependence of the spectral density of the angular velocity noise of the output signal of a fiber optic gyroscope with a noise suppression system on the difference in the normalized bandwidth of the photodetectors of the measuring channels is shown in Fig. 5.

As can be seen from the graph, decreasing the bandwidth of the photodetector of measuring channel 1 to 0.75 while maintaining the maximum bandwidth of measuring channel 2 (in the range from 0 to -0.25 $(\Delta f_{1n} - \Delta f_{2n})$) and decreasing the bandwidth of the photodetector of measuring channel 2 to 0.5 while maintaining the maximum bandwidth of measuring channel 1 (in the range from 0 to 0.5 $(\Delta f_{1n} - \Delta f_{2n})$) does not lead to a significant increase in the noise level of the output signal.

The deviation of the computer simulation graph from that calculated using the theoretical formula in the range of values from -0.25 to -1 $(\Delta f_{1n} - \Delta f_{2n})$, that is, with a decrease in the bandwidth of the measuring channel 1 in the range from 0.75 to 0, is due to the fact that expression (11) does not take into account the processes associated with a decrease in the speed of the compensating feedback loop when the bandwidth of the photodetector of the main measuring channel 1 is narrowed, leading to an increase in the spectral density of the noise of the output signal of the fiber optic gyroscope.

2.4. State of polarization. For a number of objective reasons, most fiber optic gyroscopes currently operate using plane-polarized optical radiation. Depending on the specific implementation of the fiber optic gyroscope, this is achieved either by using an optical radiation source structurally integrated with a polarizer, or by using separate polarizers or polarizers within integrated optical circuits (for example, when the radiation source signal needs to be split into several measurement channels in a multi-axis fiber optic gyroscope, this is more easily accomplished using isotropic fiber splitters, and then polarizing the radiation in each measurement channel).

The fiber optic gyroscope circuit under consideration utilizes a source with linearly polarized radiation and an extinction coefficient of at least 20 dB. This radiation source ensures the virtually complete absence of polarization states deviating from the specified value. The presence of sequentially installed polarizers in the optical circuit, consisting of polarizer-splitters and a phase modulator, each with an extinction coefficient of at least 20 dB, as well as the use of polarization-maintaining optical fiber in the Sagnac interferometer fiber circuit, ensures the polarization state is maintained throughout the entire optical path of the fiber optic gyroscope. Of importance in this study is the fact that the polarization state of the radiation incident on the photodiodes of the reference and main measurement channels is identical, meaning it contains no uncorrelated components of the optical radiation source's intensity noise. At the same time, it should be taken into account that the accuracy of the alignment of the polarization plane of all polarizers in the optical path of the fiber optic gyroscope (as well as the maintenance of their alignment over time) and the stability of h — the waveguide parameter of the fiber circuit — determines the maintenance of the ratio of the power of optical radiation incident on the photodetectors of the measuring channels. This influence can be described using Malus's law, $I = I_0\cos^2\psi$, which expresses the dependence of the intensity I of linearly polarized optical radiation that has passed through the polarizer on the intensity I_0 of the radiation incident on the polarizer and the angle ψ between the planes of polarization of the incident radiation and the polarizer. Let us introduce into the expression (7) of the spectral density of the angular velocity noise of the output signal of a fiber optic gyroscope with a noise reduction circuit the dependence of the optical radiation power incident on the photodetector of the main measuring channel 1 on the angle ψ, expressing the total error in the orientation of the plane of polarization in the entire optical path:

$$\delta\omega_n(\psi) = M\frac{\sqrt{\cos^2\psi\,\frac{1}{2}i_{n1}^2 + i_{n2}^2 + i_{n3}^2 + \frac{1}{4}(i_{n1}^2 + i_{n2}^2 + i_{n3}^2) + \frac{1}{4}i_{n4}^2(1-(\cos^2\psi))^2}}{\cos^2\psi\,\eta\frac{1}{2}P_0}. \tag{12}$$

Fig. 6 shows graphs of the dependence of the spectral density of the noise of the output signal of a fiber optic gyroscope with a noise reduction circuit (black graph) and without a noise reduction circuit (red graph) on a change in the angle ψ by ±180°.

The graphs show that:

- changing the ψ angle changes the output signal noise level in both fiber optic gyroscopes with and without a noise reduction circuit. This is explained by the same reasons as in the case of reducing the optical radiation power incident on the photodetector of the main measurement channel, discussed in Section 2.2;
- changing the ψ angle within ±10° does not significantly increase the output signal noise level.

In real-world conditions, the angle ψ typically does not exceed a few degrees. This suggests that in a fiber-optic gyroscope using a linearly polarized optical radiation source and constructed according to the circuit shown in Fig. 1, there is no noticeable effect of the polarization state on the noise spectral density level, determined by expression (12).

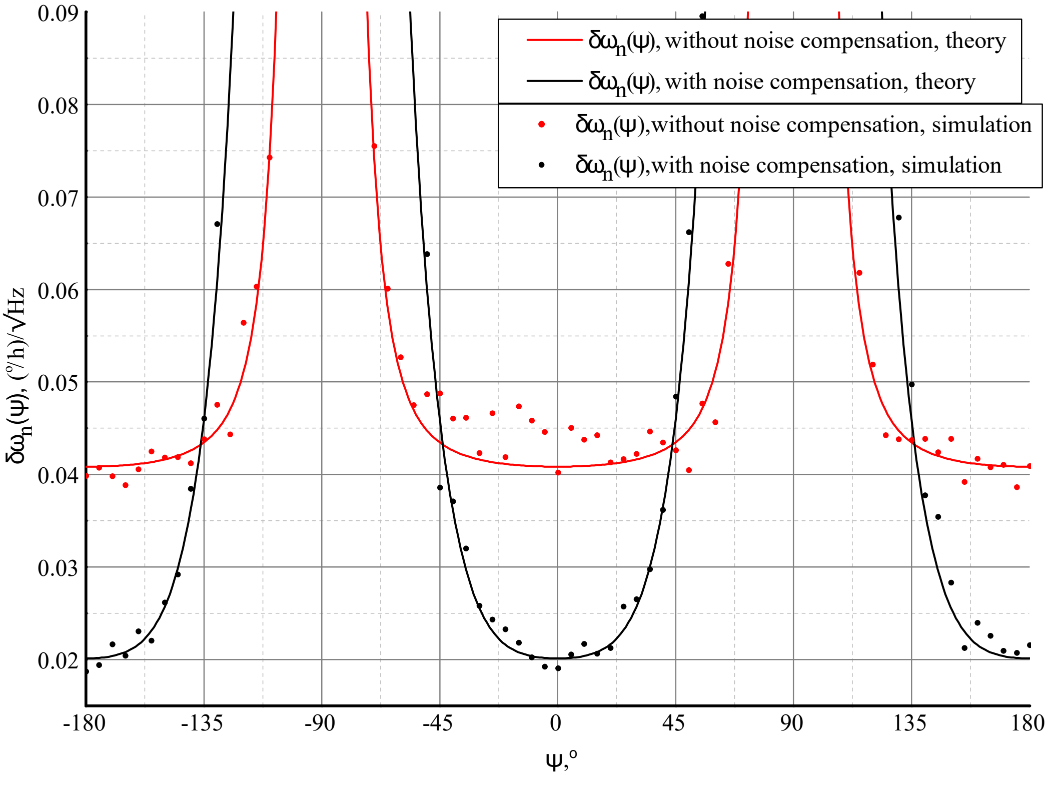

Fig. 6. Dependence of the output signal noise of the FOG with noise compensation and the FOG without noise compensation on the value of the angle ψ of deviation of the plane of polarization in the main measuring channel (color online)

Conclusion

This paper examines four key conditions that, when met, suppress the intensity noise of the optical radiation source in the output signal of a fiber optic gyroscope constructed according to the circuit shown in Fig. 1 and described by expression (6) for determining the spectral noise density of the output signal of a fiber optic gyroscope with a noise reduction circuit. Analysis of the obtained dependences of the spectral noise density level of the output signal of a fiber optic gyroscope with a noise reduction circuit allows us to determine the limits of accuracy in meeting these conditions without significantly degrading the performance of the noise reduction circuit. Analysis of the obtained dependences shows that to maintain the noise level of the output signal of a fiber optic gyroscope with a noise reduction circuit, the following requirements must be met:

1. The condition for synchronizing the signals of the measuring channels in time must be met with an accuracy of no worse than 5% of the maximum mismatch time; in the case under consideration, this corresponds to approximately ±200ns.
2. The condition for equal signal intensities in the measuring channels is asymmetrical and, depending on the nature of the deviation (changes in optical radiation power or different gains of photodetectors), has a different optimal ratio. The ratio of the average optical signal powers to the ratio of the electrical signal gains in the measuring channels should be in the range of 1...1.1.
3. The condition of equality of the bandwidth of the measuring channels is not critical; it must be met with an accuracy of at least $0.75\Delta f_{1n}$ from the normalized bandwidth of measuring channel 1 and at least $0.5\Delta f_{2n}$ from the normalized bandwidth of measuring channel 2.
4. The condition of the same state of polarization is formally fulfilled by using in the considered scheme a source of optical radiation with linear polarization in a given plane; the requirement for the accuracy of alignment and preservation of the angle ψ of the total error in the orientation of the plane of polarization must be met with an accuracy of at least ±10°.

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