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Application of Supercontinuum in Optical Gyroscopy

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The work is devoted to the study of the problem of using laser radiation in the supercontinuum mode in fiber optical gyroscopes. To achieve this goal, the following tasks were solved in the work. The physics of the process of measuring the angular velocity of an object based on the Sagnac effect is described. The factors influencing the resolution of the gyroscope are analyzed. These factors include fractional noise, unavoidable noise, and noise due to backscatter in the fiber, which can be minimized by using photonic crystal fibers and a broadband radiation source. It is proposed to use an optical supercontinuum (optical comb) as such a source. Thanks to its ultra-wide radiation spectrum, precision frequency reproduction accuracy, high radiation stability and femtosecond pulse duration, supercontinuum is considered as a promising radiation source in ranging, hyperspectral spectroscopy and imaging, tomography, and low-coherence white light interferometry. In the work of Lpischan, the physics of the supercontinuum generation process, its main characteristics. An analysis of the possibility of using an optical comb in optical gyroscopy has been carried out. Mathematical modeling of the influence of optical fiber characteristics and supercontinuum parameters on the sensitivity of a fiber gyroscope was carried out. The results of the work indicate the promise of further research on the creation of a photonic crystal fiber-optic gyroscope using supercontinuum laser radiation.

Keywords: Radiation, Fiber-optic gyroscope, Resolving ability, Femtosecond radiation, Supercontinuum, Photonic crystal fiber.

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1. INTRODUCTION

The gyroscope is the main sensitive element of stabilization, orientation and navigation devices for manned, autonomous and robotic systems. Due to the ability to respond to changes in the orientation angles of the body on which it is installed, relative to the inertial reference system, the gyroscope provides measurement of the angular velocity of rotation (Ω) and the angles of rotation of the body.

Gyroscopes are subject to requirements for measurement accuracy (sensitivity), speed, parameter drift, noise level, energy consumption, design simplification, reliability, resistance to external influences, performance under conditions of high mechanical overloads, compactness, and production cost. Currently, optical gyroscopes are increasingly replacing mechanical ones. The vast majority of serial navigation systems produced in the world are built on the basis of high-precision FOGs. The fiber optic gyroscope market is expected to grow at an average rate of 5.7% until 2026 [2].

Promising problems of optical gyroscopy include the search for new fiber-optic waveguides and radiation sources. Research on the use of photonic crystal fiber in FOG has demonstrated the possibility of reducing noise, minimizing design and reducing energy consumption with high accuracy and sensitivity in determining angular velocity [3].

The radiation source in FOGs is traditionally either a semiconductor laser diode or a superluminescent diode with a wide emission band, which is common for interference measurement systems. At the same time, there are studies devoted to the use of femtosecond radiation sources in the supercontinuum mode in metrological problems [4-8]. Thus, in [9], the fundamental possibility of using supercontinuum in optical coherence tomography was investigated. Until recently, the use of supercontinuum outside laboratory conditions was limited by the relatively large overall dimensions of the generators. However, recently, developments have been underway to create chip lasers operating in the supercontinuum mode [10]. Their use will make it possible to create compact fiber-optic information-measuring systems and sensors with new operational and metrological characteristics.

The purpose of the work is to study the problem of using laser radiation in the supercontinuum mode in fiber optical gyroscopes. To achieve this goal, the following tasks were solved in the work: the physics of the process of measuring the angular velocity of the FOG is described; problems arising during measurements were analyzed; the characteristics of the optical supercontinuum and the specificity of its generation are described; the possibilities of using supercontinuum in optical gyroscopy were investigated.

2. FIBER OPTIC GYROSCOPY

The angular velocity of rotation Ω is measured indirectly through the interference measurement of the phase difference of the rays. The FOG sensor is a Sagnac ring interferometer, which includes a source of optical radiation, a coil with a single-mode optical fiber that supports polarization, and an optical divider. The operation of the Sagnac interferometer is based on the effect of the same name and is as follows. If in a closed optical circuit two light rays propagate in opposite directions, then in the absence of rotation of the optical circuit around the axis (Ω = 0) normal to the plane of the circuit, the phase difference of both rays (φ_Ω) passing through the circuit is zero. When the optical circuit rotates (Ω ≠ 0), the phase shifts of the rays are not the same, the phase difference of the rays is proportional to the angular velocity of rotation of the circuit (Fig. 1) [11].

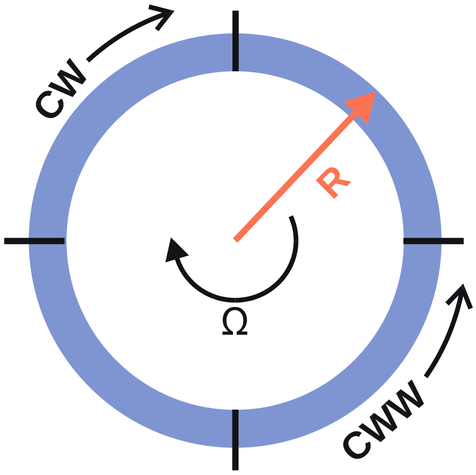

Fig. 1 – Sagnac effect: CW, CCW – beams directed clockwise and counterclockwise, respectively, R – contour radius

If the circuit rotates clockwise at speed Ω, then rays CW and CCW follow the light paths respectively:

$$L_{CW} = 2\pi R + \Omega R \Delta t \quad (1)$$

$$L_{CW} = 2\pi R - \Omega R \Delta t \quad (2)$$

where Δt is the travel time of light along the ring $\Delta t = 2\pi Rn / c$, n is the refractive index of the beam propagation medium, c is the speed of light in vacuum.

The total difference between the optical paths of CW and CCW beams is:

$$\Delta L = 2\Omega R \Delta t \quad (3)$$

From expression (3) the phase shift φ_Ω arising due to the phase difference between the CW and CCW beams is determined:

$$\varphi_\Omega = N \frac{8\pi^2 R^2 n}{\lambda c} \Omega \quad (4)$$

where λ is the operating wavelength, N is the number of turns of the optical fiber.

Expression (4) becomes the main one for measuring the FOG value of angular velocity by the number of interference fringes. It can also be used in the design of FOG to calculate the radius of the coil and the number of turns of the optical fiber of given parameters.

3. FOG RESOLUTION

The metrological characteristics of FOG, in addition to the factors described by the quantities included in (4), are influenced by a number of factors related to both the design of the interferometer and the remaining optoelectronic components of the system.

The resolution of FOG is strongly influenced by noise caused by backscattering in the fiber (Rayleigh scattering) and reflection from the surfaces of the optical elements of the system (Fresnel reflection), as a result of which scattered and primary radiation interfere in the fiber. The noise of the gyroscope output signal can be expressed by the formula:

$$N = \frac{\beta}{4} \sqrt{\frac{\alpha c}{n\sqrt{\pi}\Delta f}} \quad (5)$$

where α is the Rayleigh scattering loss in the optical fiber; β is the fraction of Rayleigh light scattering propagating in the opposite direction; Δf is the width of the light source [1].

To increase the resolution of the FOG and reduce noise, a broadband (low-coherence) radiation source is used, which worsens interference in the fiber due to the large difference in the optical path length for signal emission and Rayleigh backscattering emission. The source chosen is either multimode semiconductor lasers or superluminescent diodes with an emission linewidth of several tens of nanometers. In this case, the coherence length can be calculated using the formulas:

$$L_c = \frac{c}{\Delta f}, \quad (6)$$

where $\Delta f = c\frac{\Delta\lambda}{\lambda^2}$.

The magnitude of the characteristic L_c is the difference in the path of the CW, CCW beams, at which interference is possible. Since the line width affects the resolution of the FOG, it is worth considering the use of another broadband signal – supercontinuum.

4. SUPERCONTINUUM INTERFERENCE

Supercontinuum or optical comb is a special type of laser radiation with an ultra-wide (in some cases from ultraviolet to infrared) discrete spectrum (Fig. 2).

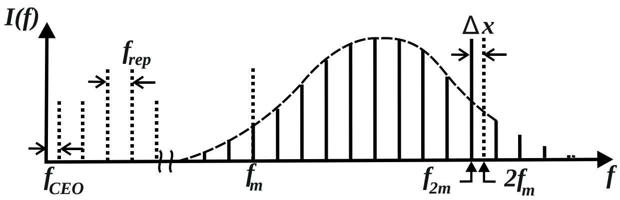

Fig. 2 – Supercontinuum diagram, where: $I(f)$ – radiation intensity; f_{CEO} – displacement of the peak with number $m = 1$ of the “ideal” frequency grid; f_{rep} – frequency interval between two adjacent peaks; Δx is the frequency of the beat signal between the signal f_{2m} and f_m

Supercontinuum is formed when femtosecond pulses propagate through highly nonlinear media, such as optical fibers. Efficient conversion of radiation into supercontinuum occurs in photonic crystal fibers, due to their unusual chromatic dispersion, which can cause strong nonlinear interaction over a significant length of the fiber, even with low radiation power of semiconductor laser diodes (< 200 pJ) a very wide radiation spectrum is achieved. The peak frequency f_m is determined by the formula:

$$f_m = f_{rep} + mf_{CEO} \quad (7)$$

The wide spectrum of radiation (7) indicates the low temporal coherence of the supercontinuum, and therefore the coherence length L_c (6). At the same time, spatial coherence in the beam cross-section plane remains high. Significant spectral power density is maintained over an interval of more than one optical octave.

Due to its wide spectrum, precision frequency reproduction, high radiation stability and femtosecond pulse duration, supercontinuum is considered as a promising radiation source in ranging, hyperspectral spectroscopy and imaging, tomography, and low-coherence white light interferometry [12-20]. The development of low-power and compact semiconductor optical comb generators will make it possible to use them in navigation devices such as FOG.

5. SUPERCONTINUUM IN GYROSCOPY

The main characteristics of FOG include sensitivity – the minimum value of the measured angular velocity. In a system with optimal sensitivity, the theoretical limit of detection of angular velocity is related to the shot noise of the photodetector. Therefore, increasing the sensitivity of FOG can be achieved by improving the design, basic elements, operating algorithms and information processing.

Using formulas (3), (4), (6), we derive a formula for the maximum value of the angular velocity $\Omega_{\max}$, which theoretically can be detected by the FOG:

$$\Omega_{\max} = \frac{c^2}{N4\pi R^2 n\Delta f} \qquad (8)$$

Formula (8) takes into account two factors affecting the sensitivity of FOG. The first factor is the length $l_0 = N2\pi R$ (Fig.3) and characteristics of the optical fiber n, (Fig.4). On the one hand, their increase leads to an increase in the sensitivity of the FOG, but on the other hand, to signal attenuation and the impossibility of interference at a certain value l_0. To estimate the maximum possible value l_0, the formula can be applied:

$$P = P_0 \exp(-\eta l) \qquad (9)$$

where P_0 is the power of the signal introduced into the fiber, l is the length of the fiber, and η is the energy loss coefficient.

Note that to reduce the effect of dispersion on the broadband signal of the supercontinuum B FOG, it is proposed to use a photonic crystal fiber with a hollow core. The advantages of using such a fiber in FOG with a superluminescent diode were demonstrated in [3].

The second factor is the source of achievement. According to (8), the larger the linewidth of the source Δf (Fig.5) (7), the higher the resolution of the FOG. According to formula (5), an increase in the noise level (N) also occurs due to interference in the fibers of direct and radiating radiation.

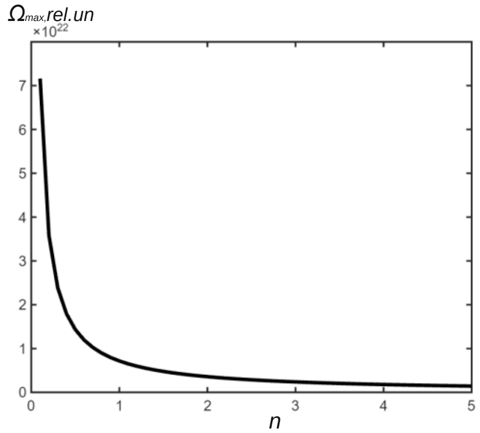

Fig. 3 – Dependence of angular velocity on the length of the optical fiber

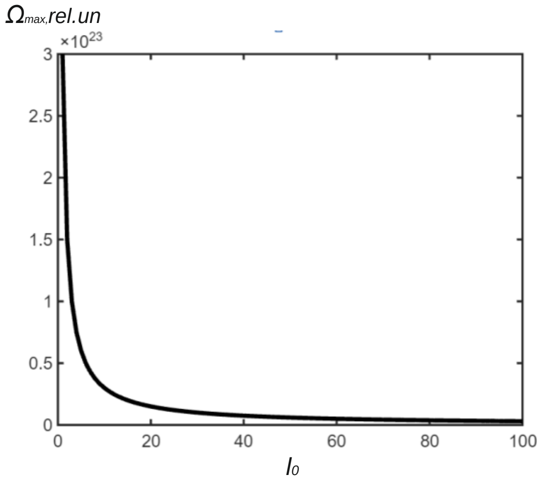

Fig. 4 – Dependence of angular velocity on the refractive index of the medium

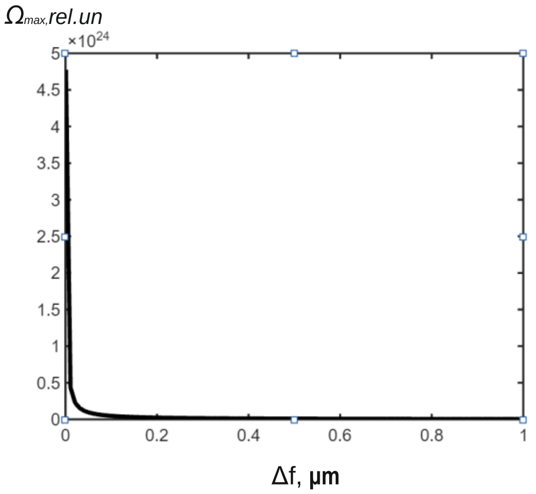

Fig. 5 – Dependence of angular velocity on the source linewidth

Thus, taking into account the first and second factors influencing the sensitivity of the FOG, we can conclude that work on creating a photonic crystal fiber-optic gyroscope using supercontinuum laser radiation is promising.

CONCLUSION

The work carried out a study of the possibility of using laser radiation in the supercontinuum mode in fiber optical gyroscopes.

The physics of the process of measuring the angular velocity of an object based on the Sagnac effect is described. Factors that influence the resolution of the gyroscope are analyzed, such as noise arising from backscattering in the fiber, which can be minimized through the use of photonic crystal fibers and a broadband radiation source, which is proposed to be a supercontinuum.

The physics of the supercontinuum generation process and its main characteristics are described. An analysis of the possibility of using an optical comb in optical gyroscopy has been carried out.

Mathematical modeling of the influence of optical fiber characteristics and supercontinuum parameters on the sensitivity of a fiber gyroscope was carried out.

The results of the work indicate the prospects for the development of fiber-optic gyrometry using supercontinuums.

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Застосування суперконтинууму в оптичній гіроскопії

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Робота присвячена вивченню проблеми використання лазерного випромінювання в режимі суперконтинууму у волоконно-оптичних гіроскопах. Для досягнення поставленої мети в роботі вирішувалися наступні завдання: описано фізику процесу вимірювання кутової швидкості об'єкта на основі ефекту Саньяка; проаналізовано фактори, що впливають на роздільну здатність гіроскопа. Ці фактори включають частковий шум, неминучий шум і шум через зворотне розсіювання у волокні, який можна мінімізувати за допомогою фотонно-кристалічних волокон і широкосмугового джерела випромінювання. В якості такого джерела пропонується використовувати оптичний суперконтинуум (оптичну гребінку). Завдяки надширокому спектру випромінювання, точності відтворення частоти, високій стабільності випромінювання та фемтосекундній тривалості імпульсу суперконтинуум вважається перспективним джерелом випромінювання в гіперспектральній спектроскопії та зображенні, томографії та інтерферометрії білого світла з низькою когерентністю. Проведено аналіз можливості використання оптичної гребінки в оптичній гіроскопії. Проведено математичне моделювання впливу характеристик оптичного волокна та параметрів суперконтинууму на чутливість волоконного гіроскопа. Результати роботи свідчать про перспективність подальших досліджень зі створення фотонно-кристалічного волоконно-оптичного гіроскопа з використанням лазерного випромінювання суперконтинууму.

Ключові слова: Випромінювання, Волоконно-оптичний гіроскоп, Роздільна здатність, Фемтосекундне випромінювання, Суперконтинуум, Фотонно-кристалічне волокно.