Nonreciprocal optical element of ring laser gyroscope based on the effect of light entrainment with moving medium

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Abstract. This article describes the use of Fresnel-Fizeau effect in order to reduce the entrapment effect in a ring laser gyroscope. The study gives an analysis of the nonreciprocal optical element impact on the gyroscope output characteristic. Moreover, it numerically estimates the method's effectiveness.

Due to a number of indisputable advantages, laser gyroscopes have received widely practical application in strapdown navigation systems. A promising area of research in this field is the development of technical methods for improving the accuracy and angular displacement sensitivity of a laser gyroscope.

In general terms, a laser gyro is an optical ring resonator, in which two independent oppositely directed traveling waves are generated. The turn of the contour having an area $S$ and perimeter $L$ in inertial space with angular velocity $\Omega$, whose vector is perpendicular to the plane of the contour, leads to a difference frequency of ingoing waves, expressed by the formula:

$$\Delta v = \frac{4S\Omega}{L\lambda} = k\Omega,$$

(1)

where $k = \frac{4S}{L\lambda}$ is a scaling coefficient of the laser gyro. Any effect that leads to a deviation of the characteristics from this dependence, is seen as an error source. Among the errors which are critical in the laser gyroscope design, there is frequency synchronization of oncoming waves (the entrapment), which is caused by microscopic defects on the optical surfaces. They serve as centers for backscattering of the energy of one beam in the direction of propagation of the other [1]. The backscattering leads to the fact that at low speeds of angular rotation $\Omega$, which are lower than a certain critical value (the entrapment threshold), traveling waves are synchronized, and the device becomes insensitive to the angular displacement.

One of the most common ways to eliminate mutual synchronization is based on the use of alternating dithering, providing torsional vibration of the gyro body around an equilibrium position with an angular velocity, which is greater than the entrapment threshold. Thus, the operating point of the device is displaced from the entrapment zone into the area where the output characteristic varies linearly (1). The analysis of the potential of current technical means shows that it is possible to increase the gyro sensitivity by reducing the oncoming waves relationship, if the refractive index nonreciprocity is provided. This method is based on introduction of the optically transparent solid medium into the resonator, the medium moving at known speed. As this takes place, in the moving medium, which is isotropic in the fixed coordinate system, there occurs "anisotropy" induced by the motion, which leads to the entrainment of light wave polarization plane. That is, there occurs an effect similar to the Fizeau-Fresnel entrainment effect [2]. A good example of practical
The implementation of this method can be found in the article [3]. As a moving medium we chose a quartz disk 20 mm in thickness with a mirror coating on flat surfaces, rotating around its axis with a frequency of 100-380 Hz. To reduce the losses inserted in the resonator, the disk was tilted at Brewster's angle with respect to the incident beam.

Similar in technical implementation to a rotating disk is the device in which the dithering oscillations are simulated by oscillations of two plane-parallel transparent prisms having a refractive index greater than a unity element, and being installed on the path of the laser beam, so that the oscillating movement is parallel to the direction of light propagation. [4]

Figure 1. Scheme of laser gyro with two movable prisms

Figure 1 shows the schematic plan of the laser gyro comprising such a device. The gyroscope resonator comprises four prisms 1, 2, 3 and 4 which guide the laser beam about a closed path 9, and the active medium 5. All together form a ring laser, in which there can exist waves propagating along the optical path in clockwise and counterclockwise directions. The prism 3 passes a small portion of the light waves in the photomixer 6 which combines the light beams into one and sends it to the photodetector (not shown) which records the interference pattern. On the laser optical path there are two plane-parallel prisms 7 and 8, installed in such a way, that the laser beam intersects their surfaces at Brewster's angle. The prisms 7 and 8 are connected to the generator (not shown), which causes them to vibrate at a frequency of several hundred Hertz and an amplitude of 2 mm, and gives them an oscillating translational motion along the direction of light propagation.

For the scheme described the wave frequency shift caused by the motion of the optical medium, will be determined by the following expression:

\[
\Delta \nu' = 4 \cdot \frac{(1 - \frac{1}{n^2}) \nu}{\lambda},
\]

where \(\nu\) is the velocity of the plates, \(\lambda\) is laser wavelength, and \(1 - \frac{1}{n^2}\) is the Fresnel dragging coefficient, in which \(n\) is the refractive index of the medium.

The time integration of the difference frequency (1) with regard to the additional frequency shift (2) for the gyroscope with oscillating prisms gives the following result:

\[
N = \int_{0}^{t} \Delta \nu + \Delta \nu' dt = k \gamma + 4 \cdot \frac{(1 - \frac{1}{n^2})}{\lambda} l,
\]
where \( N \) is the number of interference fringes that have passed in front of a photodetector in time \( t \), \( \gamma \) is the total angle of the device rotation, \( l \) is the distance at which the prisms shifted over a specified time interval.

The estimate of the value \( N' = 4 \cdot (\frac{1}{\pi}) \frac{l}{\lambda} \) is of essential interest. It characterizes an additional frequency difference between the oncoming waves, which results from the movement of the optical medium.

Since the prisms perform harmonic oscillations at a predetermined frequency \( f \), then the distance \( l \) changes sinusoidally:

\[
l = A \sin(\omega t),
\]

where \( \omega = 2\pi f \) is the cyclic oscillation frequency, \( A \) is the amplitude.

The speed of the prisms movement is incomparably small in relation to the speed of light, allowing light waves propagating in a closed circuit, to make the effective number of passes \( i \) through the optical medium in the plates semioscillation. With each passing the waves gain an elementary phase shift caused by the displacement of an optical element. Then the actual distance \( l \), passed by the prisms in semioscillation can be represented as the sum of small displacements \( \tilde{l} \), occurring in time \( \tilde{t} \), during which the light propagates in the medium:

\[
l = \sum_{k=0}^{i} \tilde{l}_k = i \cdot \tilde{l} = i \cdot A \sin(\omega \tilde{t}),
\]

where \( i = \frac{T/2}{L/c} = \frac{Tc}{2L} \) can be interpreted as the number of the laser beam passes of the resonator perimeter in the prisms semioscillation (\( c \) is the speed of light in vacuum), and \( \tilde{t} = \frac{2nd}{c} \) (\( d \) is the thickness of a single prism).

In due consideration of (4) and (5), the expression for the value \( N' \) will be as follows:

\[
N' = (n^2 - 1) \frac{8A\pi d}{nL\lambda},
\]

The experimental studies showed that the efficiency of light entrainment with the moving medium in the main approximation depends on the product \( \chi = (n^2 - 1)IV \), where \( I = \tilde{l} \) is the optical length of the path run by the laser beam in the medium, and \( V = 2A\pi f \) is the linear velocity of movement (in the projection on the beam) - maximum to modulo prisms speed. [3]

Figure 2 shows the dependency graph of the interference shift \( N' x' \) on the parameter \( \chi \), calculated at different values of the parameters \( A \), \( d \), and \( n \) optical element according to the formula (6) (\( \lambda = 633 \) nm, and \( L = 1.5 \) m).

As Figure 2 shows, dependency of the additional number of interference fringes on the efficiency parameter of light entrainment with the moving medium is close to direct proportionality. The graph deviation from a straight line can be explained by the fact that the change in the estimated value \( n \) was not equal-interval.
This article describes the method of removing a laser gyro from the entrapment zone. The method is based on the effect of light entrainment with the moving medium and can be used as an alternative to replace the dithering. We carried out an analysis of the scheme comprising a phase shifter in the form of a nonreciprocal optical element. The analysis done leads to the firm conclusion that the proposed method is effective.

Moreover, the cyclic control of the electromagnetic wave phase can be used for registration of quasi-harmonic gravity waves. The phase modulation on the frequency of the expected gravitational wave burst can increase the signal / noise ratio when using a low-frequency optical resonance occurring in the Fabry-Perot interferometer [5].

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