Ring Laser for Angle Measurement Devices

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Abstract

Angle measurement means are one of the advanced directions for the application of gas ring lasers. The requirements of ring lasers used in angle measurement devices are different, in many respects, from those used in navigation. A simple ring laser developed for implementation in high-precision angle measurement instruments is described. The main specifications are presented. Methods of the accelerated tests are imperfect for determining a term of storage, therefore, tests during a real storage term remain the most reliable. Operation of the ring lasers in angle measuring instruments during 20 years has demonstrated their high stability. Using the described ring laser the angle measurement means of accuracy that exceeds an accuracy of the existing National Standards for a plane angle can be developed.

Keywords: ring laser, laser gyroscope, goniometer

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1. Introduction

In high precision angle measurement means, photoelectric angle converters, inductive or capacity converters as well as limbs are used as angle sensors. Manufacturing of the sensitive elements (scales) for such sensors is performed on special equipment such as dividing machines. In this case, an error of the sensors includes an error of manufacturing equipment.

A ring laser comprises an angular scale set by the wavelength of laser radiation. This angular scale is a qualitatively different one in which errors of the dividing machine are absent. Use of such a scale improves essentially the parameters of angle measurement means such as accuracy, operating speed and measurement authenticity.

Ring lasers can be used in angle measurement devices of different purposes.

A significant attention is paid to the development of goniometers. For example, in [1,2,3] the design of goniometers as well as test results are described. In [4] a specialised goniometer used in workshop conditions for the measurement of polygon angles is described. In [5] the first commercial automatic angle measurement system (goniometer-spectrometer) GS1L is described. The system is designed for the measurement of plane angles and pyramidality of the prism faces as well as refractive index of optical media. This system is produced in lots and widely used at many plants and metrological centres.

The use of a ring laser for such instruments as devices for the measurement of involute profiles of tooth spiral of gear wheels [6] and a device for reproducing of linear accelerations [7] is developed.

On the basis of ring lasers it is also possible to develop automatic devices for the measurement of shaft rotation angles, devices for checking the angle parameters of limbs, modulators, circular optical encoders and other angle structures, as well as devices for determining the angles between marks, stars, geodesic and astronomical devices, laser location devices and others. The advantages of ring laser implementation in the systems for stabilisation of the rotation rate [1] are shown experimentally.

Ring lasers designed for navigation were used in the first angle measurement devices.

In connection with the specificity of the application of ring lasers for angle measurement systems and because of serial production of angle measurement means on their basis, the ring laser has been specially designed for angle measurement devices.

2. Features of Ring Laser Applications in Angle Measurement Means

Most gas ring lasers are used in military and civil navigation systems. The requirements of these ring lasers are high. For example, they must have a minimal lock-in zone, a special frequency separation unit for low angular rate measurements, they also must provide operation in a wide temperature range, in conditions of shocks, vibrations, radiation exposure, etc. The most important characteristic of the ring laser is a scale factor stability during a long period of time. There are rigid weight and dimension restrictions for such devices. Therefore, the ring lasers used in navigation systems are expensive.

The requirements of parameters of ring lasers used in industrial angle measurement means are different in many aspects. Generally, such devices operate in a narrow temperature range. They are not exposed to vibrations and shocks during the measurement process. Generally, they do not require a frequency separation unit. The implementation of the self-calibration method [8] in angle measurement devices such as goniometers allows to decrease considerably the requirements for a long-term stability of the ring laser scale factor. For most applications, the requirements of minimum dimensions and weight are not the basic ones. Therefore, a design of such lasers is simpler and they are cheaper. Furthermore, their cost falls due to a decrease the number of tests.

At the same time, additional requirements are imposed on such lasers. For example, in many cases such expensive, high-precision angle measurement devices operate for several decades. Therefore, the ring lasers implemented must have a service life of the order of 20 - 30 years. An operating life must be from several thousand to tens of thousand of hours. To obtain a high precision the ring laser must have a high angular resolution.

For angle measurement devices of different purposes several types of the ring lasers have to be developed. There are three groups of angle measurement means, which need special ring lasers.

The highest accuracy installations including National standards are concerned with the first group of the angle measurement means. As a rule it is stationary equipment without rigid requirements for dimensions of the ring lasers comprising this equipment.

The workshop angle measurement means is concerned with the second group. These are portable devices, in which ring laser weight and dimensions must be limited.

Compact mobile devices are concerned with the third group of angle measurement means. For these devices, there are rigid limitations on dimensions and weight of the subsystems including the ring lasers. Their precision is lower than that of the first and second groups.

A ring laser designed for angle measurement instruments of highest accuracy is described here.

3. Ring Laser Design

A design of the ring laser 3.970.029 is given in Fig.1.

It was developed in the Central Design Bureau (CDB) "Arsenal" (Kyiv, Ukraine) and

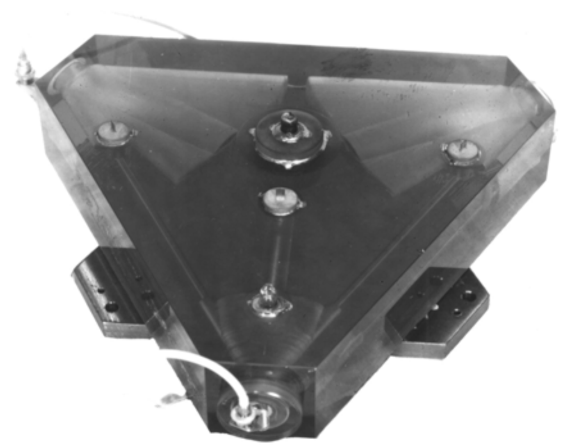

Fig.1. The ring laser 3.970.029.

made in accordance with a classical scheme.

The cavity is formed by mirrors and made as an equilateral triangle. The first mirror is mounted on a piezoelectric transducer. With its help, the adjustment of the cavity length is performed. On the second mirror, the mixing optics with the four-section photodetector for information circuit is mounted, on the third one there is a prism with the photodetector of radiation power regulation circuit.

The power supply elements are positioned in such a way that they compensate for the Langmuir drift (in the scheme: two anodes, one cathode). There is an iris in the passive channel of the cavity.

Hermetic sealing of the working volume is achieved by vacuum-tight joints. The mirrors are mounted using an optical contact. Joints of anode and cathode contacts are made by metal soldering.

Using a special adhesive, a mounting surface of the monoblock is fixed to a metal plate made of material with a low linear temperature expansion coefficient. There are three holes in the plate for its mounting in angle measurement devices.

The monoblock has three additional cavities to provide a considerable volume of a working gas mixture.

Basic specifications of the ring laser 3.970.029 are given in Table 1.

Table 1. Basic specifications of the ring laser 3.970.029

1. Monoblock material	Glass ceramic
2. Cavity shape	Equilateral triangle
3. Type of reflector	Multilayer interference dielectric mirrors
4. Length of cavity side, mm	227
5. Type of element for perimeter adjustment	Mirror shifting by the piezoelectric transducer
6. Radiation wavelength, micrometers	0.6328
7. Type of polarisation	Linear
8. Information output	Two sine signals
9. Phase shift between two information signals, electrical degrees	90 ± 5
10. Angle period value of information sine signal, period/arc. sec	1.0
11. DC pumping supply - DC voltage, V, not more than - direct current, mA, not more than	 900 3.0
12. Overall dimensions, mm - height - circumscribed circle radius	 83 160
13. Weight (with base), kg, not more than	4.3

By using the known frequency multiplication circuits two phase-shifted information signals allow the angle period value of the information signal to be decreased considerably.

4. Ring Laser Investigation Results

During investigations, the ring laser perimeter stabilisation system and radiation power stabilisation system were used.

The perimeter stabilisation system is an extreme one. A modulating signal of 11 kHz frequency is fed to the piezoelectric transducer mounted together with the mirror. A sign and value of discrepancy with respect to a Doppler curve are determined by means of a phase detector to which the information and modulating signals are fed and then a direct voltage, displacing an operating point to the top of this curve, is applied to the piezoelectrical transducer.

The radiation power stabilisation system is based on the principle of comparison of the electric signal received from the photodetector (to which one of the ring laser beams is fed) with a reference voltage. Accordingly, the pumping current of the ring laser is controlled during the discrepancy.

On the basis of information signals of the ring laser, the output pulses with a discrete quantization of 180 electrical degrees are generated. Then the counters count up these pulses.

The estimations of the scale factor and zero shift of the output characteristic have been carried out in the following way. The ring laser under check together with the electronic units for the setting of operating modes was mounted on a rotary table rotating clockwise and counterclockwise alternatively.

A turn of the rotary table through the angle 2π was registered by a stationary slit photoelectric autocollimator with a focal length of 1000 mm and a mirror reflector mounted on the moving part of the rotary table.

The measurements were carried out in cycles during which after acceleration of the rotary table determined was a number of periods of the ring laser signal every 5 revolutions while rotating clockwise and counterclockwise respectively. For one revolution of the ring laser through the angle 2π counterclockwise, a number of periods at the output is obtained as follows:

$$N_+ = KWt_+ + KW_E \sin Yt_+ + F_0 t_+ , \quad (1)$$

and at rotation of the ring laser clockwise:

$$N_- = KWt_- - KW_E \sin Yt_- - F_0 t_- , \quad (2)$$

where K is the scale factor of the ring laser; W, W_E are the angular rates of the rotary table and the Earth rate respectively; t_+, t_- are the time periods of revolution of the rotary table through the angle 2π when rotated counterclockwise and clockwise respectively; Y is a geographical latitude at which the measurements are carried out; F_0 is the zero shift frequency of the ring laser output characteristic.

The measurements were carried out at the rotation of the rotary table with an angular rate W=90 degrees/sec, latitude of measurement Y=50 degree and 27 arc min, $t_+ = t_- = t =$ 4 s.

The scale factor determination error depends on an accuracy of the photoelectric autocollimator, instability of rotary the table angular rate, quantization of the ring laser signal, etc.

To improve accuracy, an average value of period number of the ring laser signal $\overline{N}_+$ for 5 measuring revolutions of the rotary table at rotation counterclockwise (first measurement subcycle) and then $\overline{N}_-$ for the same number of measuring revolutions at rotation clockwise (second measurement subcycle) was calculated. Two measurement subcycles formed one measurement cycle.

The average values $\overline{N}_+$ and $\overline{N}_-$ for each of 50 measurement subcycles are given in Fig. 2.

The scale factor of the ring laser for each measurement cycle was estimated by the formula:

$$K = \frac{\overline{N}_{+} + \overline{N}_{-}}{4\pi}. \qquad (3)$$

Figure 3 shows the scale factor for each of 50 measurement cycles.

Between measurement cycles 24 and 25, a scale factor has suddenly changed to the relative value of 3×10^{-6}. The scale factor jump is caused by the fact that the automatic ring laser perimeter stabilization system has moved the operating point from one Doppler curve peak to the adjucent one.

Changes of the ring laser scale factor before and after the jump is represented as a linear drift, combined with random fluctuations.

Before and after the scale factor jump, its linear drift was of about 0.002 rad/sec.

To improve an angle measurement accuracy, the angular rate of the rotary table can be increased; cumulative processing of several

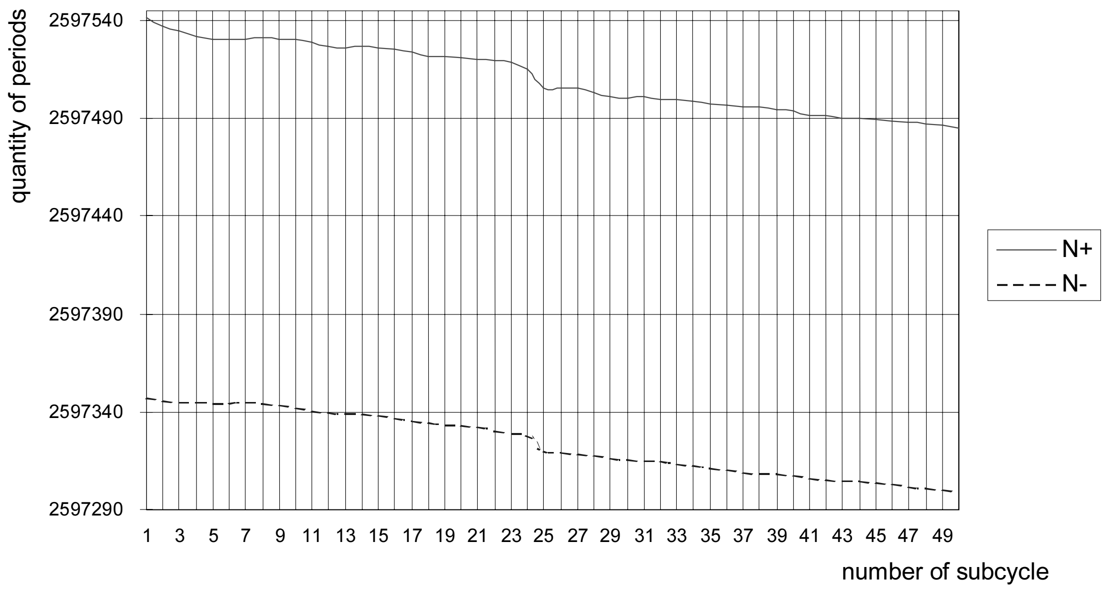

Fig.2. The average values of $\overline{N}_{+}$ and $\overline{N}_{-}$.

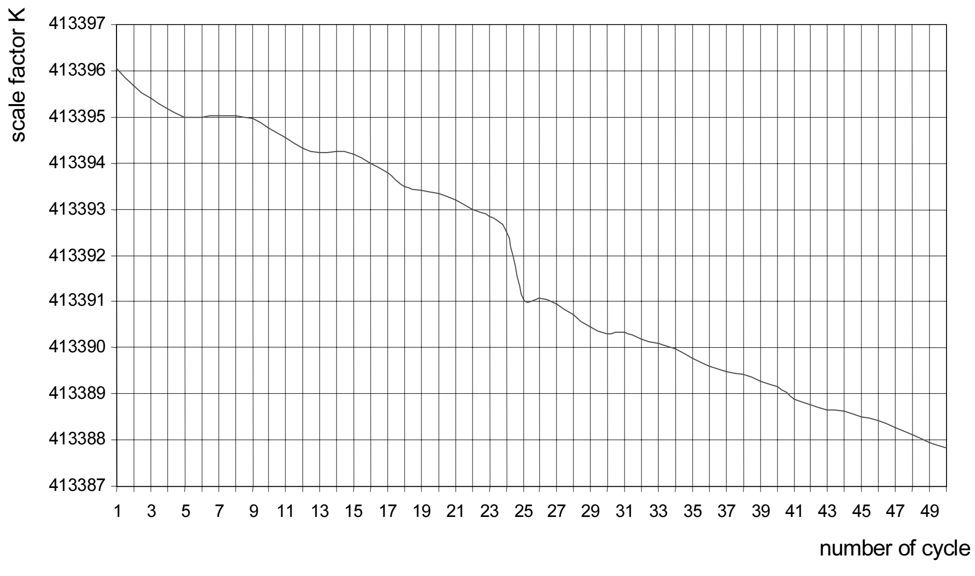

Fig. 3. Scale factor jump.

measurement cycles allows for the estimation of the scale factor drift and by means of corresponding calculations for decreasing a component of the error, caused by this drift.

Difference

$$\Delta N = \overline{N}_{+} - \overline{N}_{-} = 2KW_E \sin Yt + 2F_0 t \quad (4)$$

represents a zero shift of the ring laser output characteristic.

Figure 4 shows ΔN for 50 measurement cycles.

With the except of a transient process at the beginning of the measurements (cycles 1,2) and one cycle before and one cycle after the jump, the average value ΔN of cycles from 3 to 22 is 187.51 and that of cycles from 26 to 50 is 185.74.

Thus the changes of ring laser parameters between measurement cycles 24 and 25 result in a change of both a scale factor and a zero shift of the output characteristic.

Frequency of the zero shift of the output characteristic was estimated as:

$$F_0 = \frac{(\overline{N}_{+} - \overline{N}_{-}) - 2KW_E t \cdot \sin Y}{2t} \quad (5)$$

The average value of the zero shift for cycles from 3 to 22 was $F_0 = 0.34$ Hz; and that for cycles from 26 to 50 was $F_0 = 0.12$ Hz.

Such frequency of a zero shift is lower considerably than a frequency caused by the Earth's angular rate.

Estimation of the operating stability at clockwise and counterclockwise rotation was carried out by calculating the rms-deviation of the number of periods for 5 revolutions in each measurement subcycle.

Figure 5 shows the root-mean-square deviation (rms-deviation) at rotation counterclockwise Figure 5 shows the rms-deviation at rotation counterclockwise (continuous line) and clockwise (dotted line).

Before the scale factor jump, the rms-deviation at rotation counterclockwise is higher than that at rotation clockwise, however after this jump the rms-deviations at rotation counterclockwise and clockwise are identical. It proves that after the scale factor jump the cavity readjustment occurred.

Estimation of the rms-deviation in the case of the bi-directional rotation can be used for the check of ring laser operation.

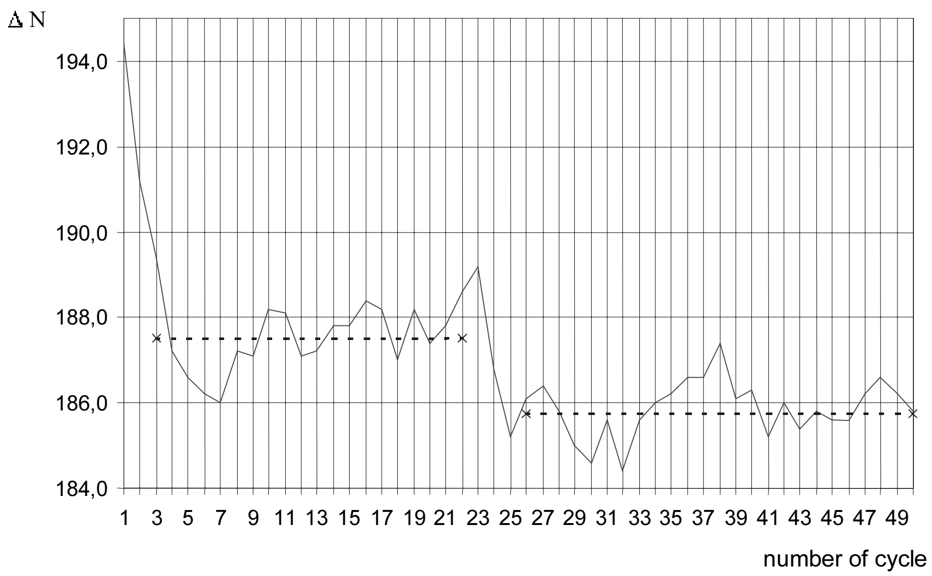

Fig.4. Difference between average values of two subcycles making one measurement cycle.

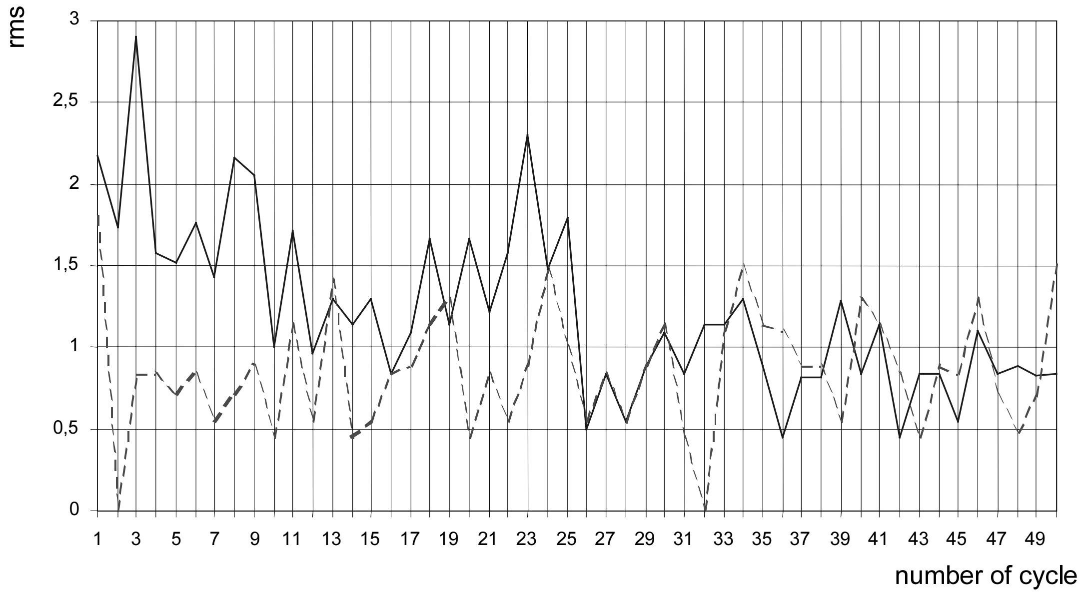

Fig. 5. RMS-deviation for each of measurement subcycles.

5. Implementation of the Ring Laser in a Goniometer

Photoelectric angle sensors are widely used for angle measurements.

Table 2 shows some parameters of the widely used photoelectric angle sensor RON 905 by "Heidenhain" [9] and the ring laser 3.970.029 by CDB "Arsenal".

The ring laser considered is used in the angle measurement system GS1L of serial production.

The accuracy of angle measurements when using angle measurement means on the basis of a ring laser is determined by many factors resulting from the parameters of subsystems of such devices. For example, for the goniometer, it is the instability of the rotary table angular rate, the registration inaccuracy of the beginning and end of the readout of the angle under check, quantization of the information signal, etc [10].

The ring laser introduces into a common angle measurement error its own error

Table 2. Parameters of the ring laser and photoelectric angle sensor

Parameters	Photoelectric angle sensor RON 905	Ring laser 3.970.029
Overall dimensions, mm • Height • Diameter • Circumscribed circle radius	 60 170 –	 83 – 160
Weight, kg	3.8	4.3
Error, arc. sec	± 0.4; with corrector AWE 1024 ± 0.2	± 0.08
Price, Euro • a sensor • a sensor with corrector AWE 1024	 6585.0 8110.0	 5500.0 –

components caused by a nonlinearity andantes caused by a nonlinearity andteristic, instability of the scale factor, signal-to-noise ratio of the information signal, etc.

The error caused by a nonlinearity of its output characteristic is easily reduced when operating in a dynamic mode at an increased angular rate. A zero shift of the output characteristic is decreased due to a design of the ring laser used and its subsystems as well as due to a current balance at the shoulders of the ring laser supply.

The angle measurements using the GS1L system are carried out at the angular rate of 90 degrees/sec. A self-calibration method [8] is used, i.e. for one full revolution of the ring laser the angle period value of the information signal is determined and then on the basis of this value the measured angles are calculated. Therefore, the scale factor stability must be provided for a time period of 4 sec. This fact considerably decreases the requirements for a long-term stability of a scale factor.

Measurements are carried out at the bi-directional rotation. A scale factor jump during the measurements results in the increase of an error. Thus, the reliable check systems for the device subsystems including those for the ring laser are required to perform the measurements. For this purpose, a difference of the same angles, measured at rotation in both directions is calculated. If the difference exceeds the allowable value the measurement is considered to be nonreliable and excluded from further processing. Such a check is simple in use and effective. It allows to register not only the degradation of the device subsystem parameters but also to supervise the external influences, for example, inadmissible vibrations of the floor on which the device is installed, random shock influences, etc.

Estimation of angle an measurement error on the GS1L system was carried out by comparison of the polygons measurement results. The measurements were conducted in Slovakian Institute for Metrology (SMU, Bratislava, Slovakia) on the GS1L system using special methods and Physical Technical Institute (PTB, Braunschweig, Germany) on an angle measurement laboratory set of PTB [11]. The comparisons have demonstrated that a difference of the measured polygon angles does not exceed ± 0.08 arc. sec.

Angle measurement accuracy of GS1L system is limited not by ring laser parameters but by the influence of other subsystems.

With GS1L system on the basis of the ring laser the National Standard for a plane angle of the Slovak republic has been introduced.

One of the most important problems in the development of angle measurement means is the serviceability of the ring laser during a long storage term.

A storage term of the ring laser is determined by gassing and gettering of getters, monoblock material, cathode, anodes, degree of cavity clearing, presence of microcracks, and so on.

Moreover, the ring laser operation is determined by the quality of mirrors and their stability, stability of parameters of the piezoelectric transducer, mixed optics, photodetectors, etc. When manufacturing the ring laser the operation of design components (mirrors, cathode, getters and so on) as well as the entire design should be predicted. There are several methods of accelerated tests (for example, radiation, thermocyclic) that give us a certain information about the laser operation during a storage term, but these methods have a low degree of authenticity. The most reliable tests are those conducted at a natural course of time.

The operation of 5 ring lasers 3.970.029 for different GS1L systems has being evaluated for the period of 20 years. The checked ring lasers were in operation from 1200 till 4500 hours and did not change their parameters. The tests on determining a storage term are continuing.

The additional theoretical and experimental investigations have shown that on the basis of the described ring laser featuring a simple design and low cost the goniometers with an accuracy exceeding the accuracy of the existing National Standards for a plane angle can be developed.

Further increase of angle measurement accuracy by using the described ring laser can be achieved first of all due to the improvement of subsystem parameters of an angle measurement device, and due to the application of more perfect electronic circuits for perimeter and radiation power stabilisation as well as corresponding information processing with taking into account an estimation of the scale factor drift of the ring laser.

References

1. Batrakov A.S., Butusov M.M., Grechka G.P. and others, edited by Loukianov D.P. Laser Measurement Systems. - Moscow: Radio i svjaz. (1981) p. 456 (in Russian).
2. Filatov Yu.V., Loukianov D.P. and Probst R. Dynamic Angle Measurement by Means of a Ring Laser, Metrology, (1997) **34** 343-351.
3. D. Loukianov, R. Rodloff, H. Sorg, B. Stieler. Optical Gyros and their Application, Published in May 1999.
4. Vanyurikhin A.I., Zaytsev I.I. Soviet Journal of Optical Technology, (1982) **9** 28-31.
5. Angle Measurement System GS1L. Technical Specification and Operating Instructions. Ukraine, Kyiv, Central Design Bureau "Arsenal".
6. Gafanovich G.Y., Gatskalova T.G., Kupko V.S. and all. Ukr. Metrol. J. (1996), **4** 50-56 (in Russian).
7. Artemiev I.M., Blanter B.E., Kovchin S.A. and all. Proc. of Metrological Institutes of USSR (1977) **205** 3-7 (in Russian).
8. Catherin J.M., Dessus B., French patent No. 1511089, issued 14.12.1966. cl. G 01 C.
9. Circular of company Heidenhain "Drehgeber und Winkelmessgeraete".
10. Bezvesilnaja E., Zaytsev Y. Proc. of Gyro Technology Symposium (1999) Stuttgart, Germany, 8.0-8.9.
11. Mokrosh J., Probst R. Just A. Vergleichsmessungen an Winkelnormalen zwischen dem SMU Bratislava und der PTB Braunschweig. PTB - Mitteilungen **106** 5/96, 337-343.