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20 th SAINT PETERSBURG INTERNATIONAL CONFERENCE ON INTEGRATED NAVIGATION SYSTEMS

27 - 29 May 2013

Saint Petersburg, Russia

CO-SPONSORED BY:

- SCIENTIFIC COUNCIL OF THE RUSSIAN ACADEMY OF SCIENCES ON THE PROBLEMS OF MOTION CONTROL AND NAVIGATION
- RUSSIAN FOUNDATION FOR BASIC RESEARCH
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In the present publication the invited, plenary and poster papers of the 20th Saint Petersburg International Conference on Integrated Navigation Systems (27 – 29 May, 2013) are presented.

*The poster papers marked with *.*

Editor-in-Chief

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ISBN 978-5-91995-020-2

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Abstract

Key words: laser gyroscope, the Sagnac effect

This paper describes the history of a laser gyroscope, which originated from one of the fundamental physics area – optics of moving bodies, and in particular, the Sagnac effect. Background and prediction of the first ring laser gyro (RLG), which opened a new era of wave gyroscopes, is described. Its scientific basis was Einstein's theory of stimulated emission, which was expounded by the Nobel laureates N.G. Basov, A.M. Prokhorov and C. Townes that created the world's first quantum generator (maser) – the predecessor of coherent optical radiation – laser. That was enough to create the first laboratory model of the ring laser gyro in 1962. The history of the RLG construction concepts from its first samples of minimal configuration to multi-frequency Zeeman modifications with nonplanar resonators is observed. The leading role of a ring laser gyroscope in the creation of inertial measurement units, strapdown inertial and integrated navigation systems is shown. Special attention is paid to the current state of the gyro market in general and the place of RLG among them. The general trends in the inertial sensors market development are highlighted. The main producers of either RLGs or systems based on them are mentioned. Information on the development of ultra large ring laser gyroscopes is provided.

Introduction

The era of 'iron' gyroscopes opened up by J.B.L. Foucault's discovery in 1851(actually, by J.G.F. Bohnenberger in 1817) gave mankind a clue to the mysteries of the outer space and depths of the World Ocean, and formed the prerequisites for the development of a new generation of navigation and control systems for various civil and military applications. During the years of the cold war 'iron' gyroscopic technologies reached its peak from which the level of military confrontation of the two world systems and the possibility to keep a check on it were assessed.

By the middle of the 20th century the academic science, both in the USSR and USA, developed the theory of quantum molecular generators that provided the basis for a new generation of devices – lasers. Their advent in the depths of military and industrial complexes allowed fantastic projects of laser hyperboloids, highly efficient guidance facilities to be designed and put into practice, new production procedures and techniques to be developed, etc. The capability of the country to elaborate and develop laser technology was indicative of its greatness and power no less than possession of nuclear weapons and achievements in space exploration. Starting from 1961 lasers of different types occupied a firm place in optical laboratories. The advent of the first optical gyroscopes was predetermined.

This paper is a brief history of the laser gyroscope development. It considers the prerequisites and conditions in which laser gyroscope was coming into existence, presents various concepts of their optico-physical schemes, describes problems, methods and ways used to settle them.

The origins of laser gyroscopes

The background for the optical gyro was based on research in the optics of moving bodies. Almost all of the optical effects of moving bodies were discovered in research aimed at understanding the properties of the "ether" – a kind of medium that is responsible, according to most scientists in the late XIX century, for the propagation of light. Results of experiments designed to study the properties of the "ether" determined the creation of Einstein's special theory of relativity, expressed in 1905 in the paper "On the electrodynamics of moving bodies" [2].

One of the experiments on the properties of "ether" was the one carried out in 1913 by the French physicist Georges Sagnac. Through the research on the detection of "ether" dragging by rotating machinery he invented the "vortex optical effect", allowing to measure the speed of object rotation in reference to the inertial space by optical methods [3]. G. Sagnac in his experiment has found an association between the displacement of the interference pattern, formed at the output of an optical interferometer with a closed loop (ring interferometer) by counter propagating light beams, and its angular velocity. Later experiments by A. Michelson and H. Gail demonstrated the ability to measure the speed of the Earth rotation using a ring interferometer with a perimeter of 1.9 km. Broad prospects were opened in the navigation area for the gyroscope with no mechanical parts. However, the Sagnac effect for a long time remained unclaimed, primarily because of its low sensitivity. In the Sagnac experiment an interferometer with an area of 866 cm^2 had been rotating at 2.3 rev/s and the offset of the interference pattern was only 0.04 of the band. So the optic gyro has not been claimed for the decades.

The situation changed dramatically with the development of quantum electronics and the creation of the first laser. Initial discovery in the development of quantum electronics was the prediction of stimulated emission phenomenon made by Albert Einstein in 1916. First stimulated emission was obtained in 1950 by American physicists E. Purcell and R. Pound, in experiments to create overpopulation in nuclear spin systems. In 1953–1954 N.G. Basov and A.M. Prokhorov (USSR) and, independently, Townes (USA) achieved the radiation of the centimeter range on the molecules of ammonia. Thus was created the first quantum generator – maser (maser – microwave amplification by stimulated emission of radiation). In 1955, Basov and Prokhorov proposed three-level method for obtaining an inverse population of the molecular levels. Functional three-level solid-state quantum amplifiers were created in 1957–1958 in the USA and the USSR. N. Basov, A. Prokhorov and C. Townes were awarded the Nobel Prize in physics in 1964 for their results.

Further development of quantum electronics was tended to the optical range. In 1958, Prokhorov and R. Dicke (USA) put forward the idea of an open cavity, which was an important factor in the creation of solid-state and gas quantum generators – lasers (laser – light amplification by stimulated emission of radiation). The first laser was created by T. Maiman (USA) in 1960 using an open resonator and synthetic ruby crystal (the wavelength of the radiation was 0.7 μm). Six months later A. Javan, W. Bennett and A. Herriot (USA) constructed the first He-Ne laser.

Then, at the time of quantum-optical technologie's first steps the scientific world was agitated by numerous laser effects, discoveries and hypotheses that followed the emergence of laser technology. Numerous reports about mastering more and more new laser media and wave lengths gave birth to adventurous prospects for creation of superpowerful 'hyperboloids', holographic television, and so on.

It is no wonder that against this background a report about the possibility to create radically new laser-based measuring devices, laser gyros made by the future Nobel Prize winner A.M. Prokhorov in the Physics Institute of the USSR Academy of Sciences in 1962 was passed unnoticed. But a team of young engineers (V. Kuryatov, E. Nasedkin, G. Koshkin) from the Research and Development Institute (R&DI) of Applied Physics treated the idea of developing such devices seriously.

It is worth noting that the experimental studies of the G. Sagnak effect in the RF range carried out in the USSR by N.L. Bernstein 10 years before the first lasers appeared correspond in essence to modern fiber-optic gyros in architecture [4]. However at that time there were no prerequisites for extending these studies to the optical range. Nevertheless, the priority of I.L. Berstein, who had anticipated the fiber-optic gyro, is respected by both Russian and US societies..

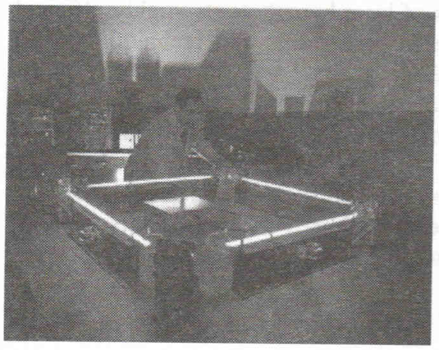


Fig. 1. W. Macek with the first laser gyro (1963)

In 1962 Rosenthal (USA) proposed [5], and W. Macek and D. Davis (USA), implemented the first He-Ne laser with a ring resonator (ring laser), which started the development of laser gyroscopes (Fig. 1) [6]. The active medium was a He-Ne mixture which filled four discharge tubes. Along with reflecting mirrors this construction was a closed rectangular cavity with sides of about 1 m. The resonator operating frequency was chosen for reasons of obtaining the maximum gain that was achieved at a wavelength of 1152.3 nm. Laboratory prototype demonstrated the possibility of measuring the angular displacement with respect to inertial space with sufficiently high sensitivity.

It should be noted that in the early 60s laser gyroscope technology had to win recognition side by side with mechanical ("iron") gyroscopes over the decades of its history, . They were fully consistent with the ideology of platform inertial systems that were prevelant at that time . There had existed a developed theory, production basis and, what is of particular importance, the time-proved traditions based on incontestable authorities. That is why timid attempts of enthusiasts to develop investigations in laser gyroscopes failed as a rule, and were never even made in a number of ministries.

Laser gyroscope technology was 'luckier' at the enterprises where there was no pressing authority of traditional gyroscopists but they had optical and electrovacuum production basis. Thus the Applied Physics R&DI headed by L.N. Kurbatov showed the most effective start in developing RLGs. However later the research conducted on a far larger scale in the R&DI "Polyus" (General Director M.F. Stelmakh) culminated in batch production of RLGs.

The first Soviet RLG was made in the mid 1963. It was suspended from the ceiling of the room (like the Foucault pendulum) in order to provide biasing and isolation from the building foundation. It did operate successfully despite many technological restrictions and inconveniences (limited service life of gas-discharge tubes, invisible infra-red radiation, a semi-conducting radiation detector made of exotic indium and stibium that was to be regularly cooled by liquid nitrogen and kept everybody alert because of its fragile construction, use of high-power 300W high-frequency pump oscillators rather dangerous for health, etc.) [7].

6 months later with the next mock-up that operated in the visible range of the spectrum it became possible to measure the Earth's rotation, study synchronization of counter propagating waves, feel the influence of the magnetic field, and test various ways of the linearization of RLG output characteristics.

In 1965 N.V. Kuryatov defended the first applied Candidate's thesis on RLG in the USSR, its essentials being topical even today. Works in the field of laser gyroscopes have received further development in a number of organizations in Moscow and Kiev. The R&DI "Polyus" worked in two directions: the first developed the monoblock RLG on total reflection prisms (TRP) under the supervision of V.N. Kuryatov, and the second was working on creation of RLG on the Zeeman effect led by Boris Rybakov. V.A. Zborowski in Research and manufacturing association "Astrophysics" studied monoblock RLG with mirrors and nonreciprocal Faraday element, which became the prototype for the gyros that were serially produced at the factory "Arsenal" (Kiev) under V.I. Buzanov's supervision.

It is no secret that the most significant scientific and practical results in laser and fiber-optic gyroscopes were achieved in the depths of military and industrial complexes of the leading states. Hence the details of the technical processes, tests, as well as practical applications concerning RLG, were and in many aspects still remain secret. This situation was aggravated by the 'iron curtain' that separated the NATO and Warsaw Pact countries. Needless to say that the international scientific and technical cooperation and assistance of RLG researchers and designers was impossible. Although there was a great number of publications devoted, first of all, to the theory of optical gyros, many basic details concerning the production and new technologies were not opened, and the period between the laboratory/prototype models and commercial production turned out to be rather long.

The history of Honeywell, one of the leading companies in the world in laser gyroscope technology is evidence that considerable commercial progress can only be made through effective mastering of military and commercial markets or, in other words, dual technologies. Simultaneous development and introduction of a great number of devices and systems provides decrease in their cost which, in its turn, results in increase of sales. That can be illustrated by the results of Honeywell activities in the period from 1965 to 1994 (fig. 2) [8].

Indeed, as follows from Fig. 2, the first stage of the investigations and developments which lasted rather a long time from 1965 to 1979, could only have been realized under the government financing which was evidently provided until the first deliveries of the laser navigation equipment for the Boeing 757/767.

Subsequently, the results obtained enabled a new series of RLGs with a more reduced size and weight and the quantity of the production sharply increased, at the same time the costs became lower. By 1992 the ratio between the commercial and military production was more than 10:1, whereas the cost per unit was reduced by a factor of 6.5 from 1981 to 1992.

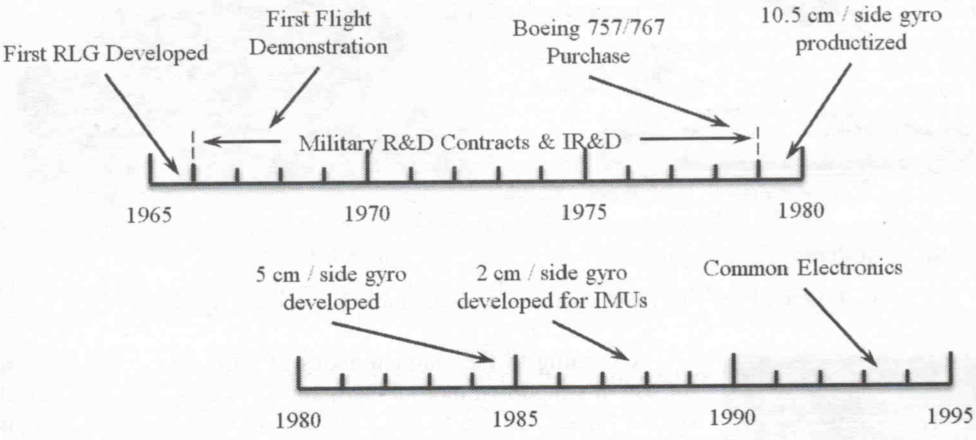


Fig. 2. Research and development of the RLG by Honeywell (1965 – 1994)

The history of laser gyroscopy development at one of the leading enterprises in the former Soviet Union, the Central Design Bureau (CDB) and the plant "Arsenal" differed to some extent (Fig. 3).

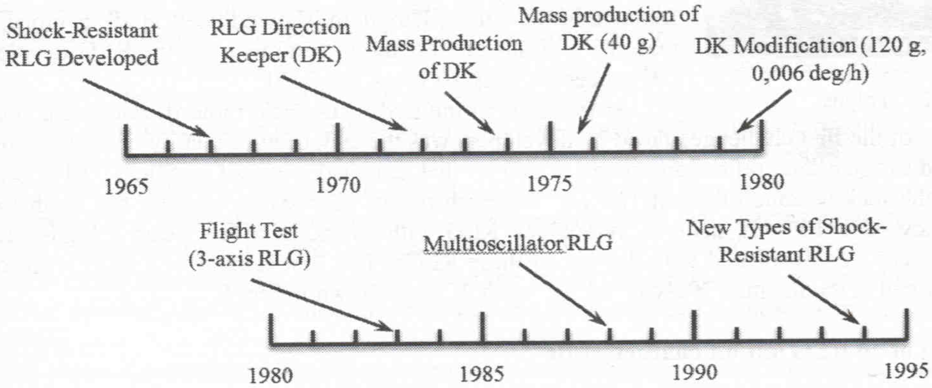


Fig. 3. CDB and "Arsenal" RLG technology development history (1969–1994)

Here the development of both prototype and serial products were systematically financed by governmental orders which had little or no provision for development of civil commercial technology. The planned production and tight control were targeted to make the research and development periods shorter, to improve the tactical characteristics of the devices developed, as follows from Fig. 3.

The first laser gyros

Soon after the first demonstration of a ring laser gyroscope the development of its semi-commercial samples had begun. One of the first models was demonstrated by Sperry Marine (aquired by Lockheed Martin) in the mid-60s. Its photo and construction scheme is shown in fig. 4 [9].

RLG was the modular type and included the He–Ne active medium with a wavelength of 1152.3 nm, triangular loop with sides of 7.62 mm, formed by TRPs, Faraday cell for artificial non-reciprocity and piezoelectric actuator on one of the prisms to monitor and control the path length. The resonator was made of aluminum and additionally equipped with a temperature sensor and a set of heaters. They maintained a constant temperature of 65 °C, thereby providing stability of cavity geometrical dimensions. The whole assembly was placed in a case provided with thermal and magnetic shielding to maintain stable operating conditions. Therefore it was the first sample of a gyroscope with no spinning rotor.

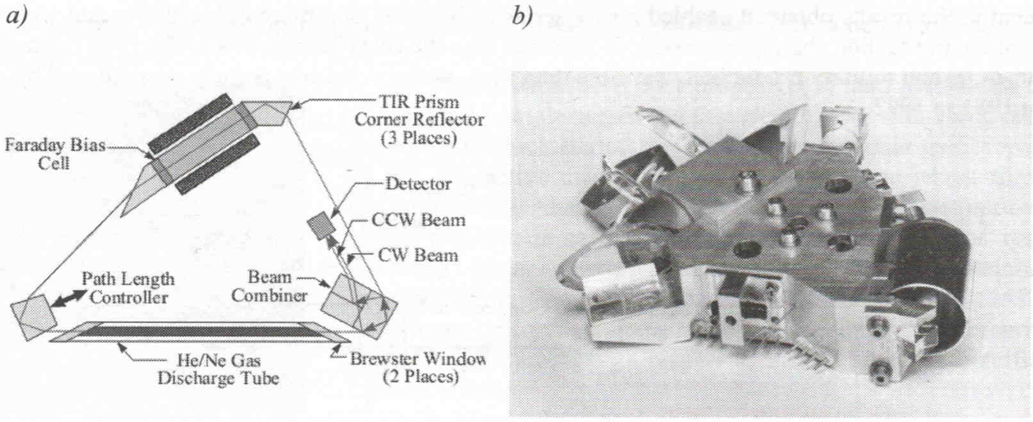


Fig. 4. One of the first laser gyroscopes: schematic (*a*) and the appearance (*b*)

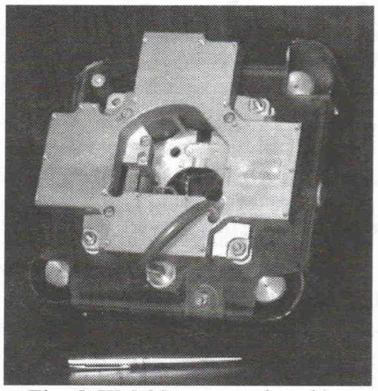


Fig. 5. KM-22 gyro produced by R&DI "Polyus"

According to the characteristics of RLG it was the most suitable gyro for use in strapdown inertial navigation systems (SINS). Their development started rapidly owing to the forthcoming of high-speed computing. It was attractive to put a triad of gyros into a single case and form an inertial measurement unit (IMU). Despite some shortcomings (tube lifetime less than 1000 hours, a large readiness time, high power consumption) developed gyroscopes were quite popular. In particular, it was tested in NASA, as well as in laboratories of Naval and Air Forces.

Around the same period, the ring laser gyro was an object of interest in Europe. In 1967 Farnborough, United Kingdom, hosted the first European demonstration of the laser gyro. A sensor designed for the Ministry of Defence of the United Kingdom, showed itself in all its glory, but for some reason it did not interest the government. So the RLG development in the UK proceeded only 10 years later [10].

At this time in the USSR the most rapid development started at R&DI "Polyus". One of the first challenges faced by developers was the lack of high-quality optical mirrors. Therefore, it was decided to use a total reflection prisms, which by that time had a loss of less than 0.01%, which provided the value of the lock-in zone of about 100 Hz. Research results allowed to measure the Earth rotation with a record accuracy of 8×10^{-4} °/h, using a monoblock RLG with TRPs. In a few years a high-precision marine navigation system was developed with the use of these RLGs. The first sample of a RLG with total reflection prisms, developed at the Institute "Polyus" by Kuryatov V.N. is shown in Fig. 5.

Linearization of an RLG output characteristic

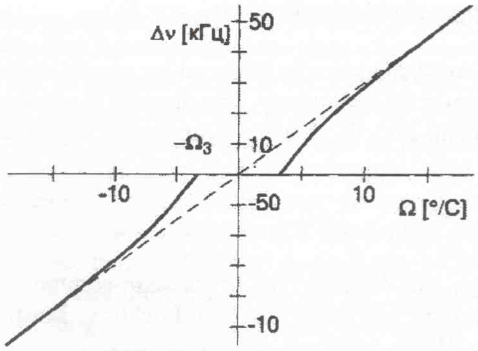


Fig. 6. Output characteristic of RLG: $S = 0.017$ m^2, $L = 0.6$ m, $\lambda = 0.63$ μm

It should be noted that the first years of laser gyroscope there was a question on how to eliminate lock-in zone or mutual synchronization of. According to the conventional RLG model it consists of two quasi-autonomous oscillators exciting counter-propagating waves that will inevitably pass through some inhomogeneities in the cavity that scatter the opposing waves. Scattered radiation plays a role of a synchronizer that locks the frequencies of CW and CCW beams together. This effect is observed at low angular velocities, where synchronization of counter-propagating waves leads to their strong coupling. Consequently the counter-rotating frequencies become equal and the difference frequency becomes zero. Typical output characteristics of RLG are shown in Fig. 6 [11]. Lock-in and nonlinear zones are clearly observed. Thus, the elimination of the lock-in zone tends to linearize the output characteristic.

There are several ways of solving the abovementioned problem:

1. Rotation of RLG at a constant angular velocity.
2. Adding a nonreciprocal phase-shifter (NPS) based on the Fizeau, Faraday effect or others into the cavity,
3. The use of vibratory angular motion, which was called mechanical dither.

4. Using the Zeeman splitting of the frequencies of counter-propagating waves in a magnetic field.
5. Multi-frequency modes.
6. Using the natural nonreciprocal phase-shifter [12].

The R&DI "Polyus" developed the technology in several directions. V.N. Kuryatov led the team to develop a series of gyroscopes named KM with a mechanical dither, and at the same time A.V. Melnikov, B.V. Rybakov and others developed the ones with different types of NPS or Zeeman splitting of the counter-propagating waves, that is based on the non-planar resonators.

RLG Technology in 70s

Most RLG applications required a sensor with the capability to turn-on from a cold start and be ready to operate within minutes. The initial RLG product did not satisfy this requirement. Furthermore, the power consumption of this design exceeded the desired level for many applications. A major RLG redesign was required to reduce sensor turn-on/stabilization time and power consumption. Elimination of these shortcomings has become one of the key challenges for the American scientists in the 70s [9].

The thermally-controlled aluminum optical cavity configuration was responsible for both the long turn-on thermal stabilization time and high power consumption. A temperature-insensitive RLG sensor design was needed to eliminate the requirement for active thermal control with heaters.

The cavity structure was the primary component requiring redesign. The aluminum cavity material was replaced with a glass/ceramic material that had a near zero thermal expansion rate. The variation of glass/ceramic cavity dimensions with temperature was well within the path length controller's range of adjustment. This change required the development of new fabrication/assembly techniques and a glass machining facility.

The prism corner reflectors also contributed to RLG temperature sensitivity. The refractive index of the prism glass changed with temperature and produced a corresponding change in the optical path length (measured in wavelengths) of a laser beam passing through the prism. Although this nominally had the same affect on both the CW and CCW beams, the path length control loop had to continually compensate for the path length changes until thermal stabilization was achieved. Replacing the prisms with multi-layer dielectric (MLD) mirrors solved this corner reflector problem. By this time, MLD technology matured to the point where high reflectance (>99.9%) mirrors became readily available. These front surface mirrors completely eliminated the thermal sensitivity associated with propagating through the bulk prism optical material.

The Faraday Bias cell, like prism corner reflectors, was temperature sensitive because it introduced bulk optical material to the laser beam path. Fortunately, Sperry gyroscope's R&D efforts resulted in the timely development of a magneto-optic bias mirror. The operating principle of this device was based on the magneto-optic Kerr effect [13]. It was a front surface mirror with a metallic layer that, when a magnetic field was applied to it, produced a non-reciprocal phase difference between the CW and CCW beams reflecting off it. The implementation of the magnetic bias mirror simplified the sensor design by replacing both the Faraday bias cell and one corner reflector. However, the magnetic bias mirror introduced somewhat more optical loss to the resonant cavity.

All of the above improvements as well as improved gas discharge tube were implemented in a rapid reaction RLG design that satisfied the requirements of many potential applications. It had a turn-on/stabilization time on the order of a few minutes and low power consumption. Block diagram and the appearance of one of these sensors are shown in Fig. 7.

a) *b)*

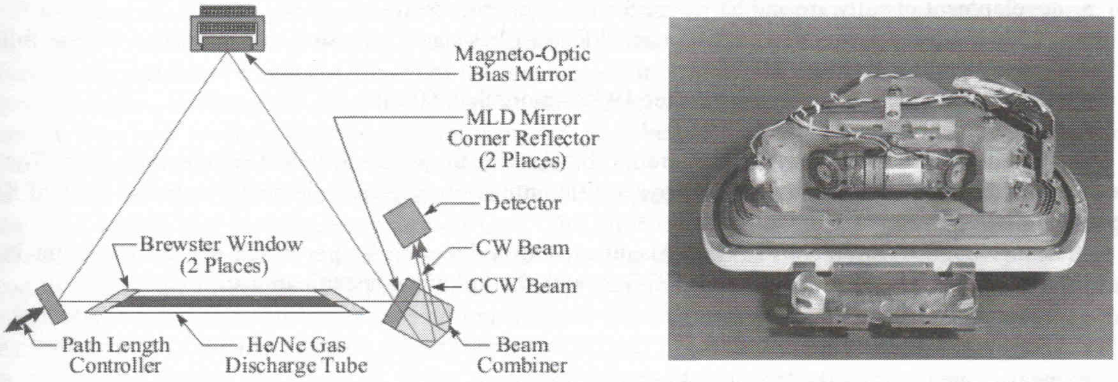
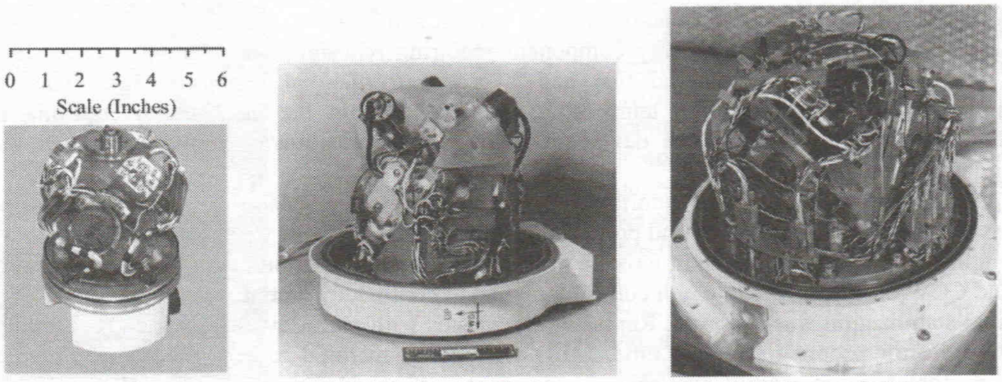


Fig. 7. Rapid-reaction RLG: schematic (*a*) and the appearance (*b*)

Special attention should be paid to the proposition of de Lange [14] on the use of four-frequency mode in order to reduce the coupling of counter-propagating waves. U.S. patent [15] issued for the differential RLG (Differential Laser Gyro System), has established commonly known abbreviation DILAG for the four-frequency RLG. Development of the first DILAG examples refers to 1977 [16]. Further, this gyroscope was developed in Litton and Raytheon (technology later aquired by Litton which was aquired by Northrop) where it was named ZLG (Zero Lock Gyro) and gained the popularity in many systems.

In the mid 70s Sperry (Department of Lockheed Martin) has developed several IMUs with three or more axes. Clustered RLG sensors were designed with three RLG cavities machined into a common glass/ceramic block. The mutually orthogonal optical cavities were interwoven to maximize the cavity size that could be accommodated within the specified IMU volume. This technique provided a clustered RLG sensor with a volume about half that of an equivalent grouping of single-axis RLGs. Accelerometers, one for each RLG, were also mounted on the clustered RLG cavity or case to form a multi-axis IMU. Clustered sensor designs provided other benefits in addition to the enhancement of IMU performance per volume. The monolithic cavity structure ensured the precise and stable alignment of RLG sensitive axes. It was also less expensive to build because it had fewer parts than designs using individual single-axis RLGs and enabled concurrent assembly of three axes. Separate clustered RLG designs were developed for missile, aircraft and spacecraft applications. (see Fig. 8.)



3-Axis Missile RLG | 3-Axis Aircraft RLG | 6-Axis Spacecraft RLG

Fig. 8. Clustered RLG Sensors made by Sperry (end of the 70s)

Meanwhile in the Soviet Union the Central Design Bureau and the plant "Arsenal", Kiev was actively involved in the development of RLG. Having their own manufacturing base, they had the opportunity to either engage in the development of the RLG theory new concepts of their design, or sharpen the technological aspect of production. The work was conducted in close collaboration with the leading R&DI and manufacturing enterprises of the former USSR, the main lines being as follows:

- development of multilayer mirrors;
- development of nonreciprocal elements based on the Faraday effect;
- development of techniques for vacuum treatment of LG resonators;
- development of special-purpose glass/ceramics with extremely low linear expansion factor;
- development of cold cathodes;
- establishment of research, production and test laboratories at the Production Association *Arsenal*;
- development of software and hardware for LG data processing, etc.

Since 1974 the mass production of RLG named KOG-1 has started. Sensors characteristics were as follows:

- readiness time – less than 60 msec;
- shock resistance – more than 4 g (since 1976 – more than 60 g);
- measurement error – 0.5°/h.

The RLG is built as a massive glass/ceramic block with three identical RLGs contained in it. The RLG sensitive axes are aligned. Each sensor employs a differential nonreciprocal element. A general view of KOG-1 is shown in Fig. 9, a.

Starting in 1976, the plant has been manufacturing a direction keeper based on KOG-1. Later in 1978 they started production of a modified RLG (KOG-2) with the following specifications:

- readiness time – less than 20 msec;
- shock resistance – more than 120 g;
- measurement error – 0.0056°/h (subject to calibration).

In the years 1975-1981 new RLGs for ground mobile vehicles were developed to provide the gyrocompassing mode. As in the case of the first constructions, the device used a differential nonreciprocal element. The RLG named "Fanza" operated with reverse about the vertical axis. The gyrocompassing error was $\sigma \leq 8'$ over 10 min of operation. In the regime of current orientation measurement the course, pitching and roll angle error was $\sigma = 0,3$ °/h. Fig. 9, b shows a general view of the device. It served as the basis for a three-axis RLG unit developed in 1978-1981 (Fig. 9, c).

a) *b)* *c)*

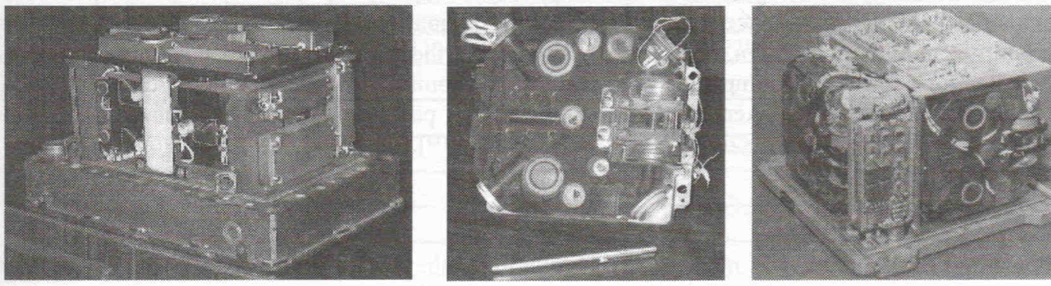


Fig. 9. RLGs produced by "Arsenal" KOG-1(*a*), Fanza (*b*) and 3-axis IMU (*c*)

In Europe, the RLG development had a similar way and in the mid 70s Sagem (France) and Marconi (UK) started the development of RLG-based SINS. But the golden age of those was reached only in the next decade, which some researchers call the "Decade of the laser gyroscope" [10].

1980s

Over the years the systems on the basis of RLG has found more and more applications. However, one RLG application required a missile grade sensor capable of surviving and operating in very severe environments. This application had a short mission time and required an IMU that could turn on within seconds and perform under extreme vibration and shock conditions.

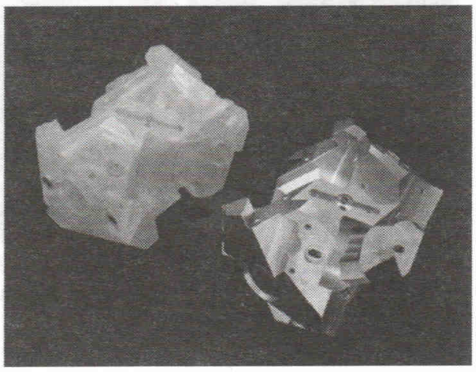


Fig. 10. Glass/ceramic cavity for traditional gyros and the metal one for shock-resistant

A special RLG sensor was developed for this application that took advantage of modular RLG design flexibility [9]. There was great concern that the standard glass/ceramic cavity structure would deflect and possibly fracture when exposed to the vibration and shock environment for this application. The density/modulus of elasticity ratio for this material was very high. A stress analysis indicated that the expected high-g loads on the massive cavity would produce stresses in excess of the glass/ceramic is elastic limit and result in structural failure. Based on this result, a survey was performed to identify a suitable cavity material with a low density/modulus of elasticity ratio. The survey concluded that a low density metal was the optimum cavity material for this application. However, although this material had the required mechanical properties, it violated traditional RLG design criteria in two ways.

First, the metal was an electrical conductor. All integral RLG designs required an electrical insulating cavity material to accommodate the gas discharge. However, the modular RLG design, with separable discharge tube, did not have this restriction. As previously discussed, initial modular RLG cavities were made of metal.

Second, the metal had a high coefficient of thermal expansion. Did this mean that a thermal control loop was required to stabilize the temperature of the cavity and its dimensions as in the initial modular RLG design? No, the mission time was so short that the mission was over long before the cavity could change temperature. A metal cavity was suitable for this special application. (see Fig.10.)

In addition to selecting the resonator material the developers had some other problems. Ultralow sensor mission time needed near-instantaneous turn-on time. The discharge tube might take several minutes to ignite after the RLG was off for a day or more. The ignition delay was due to the fact that an initial free electron was required to initiate the discharge [17] The tube ignition problem was solved by installing a small radioisotope inside the tube to serve as a constant source of ionization. With this modification, tube ignition time was limited only by the rise time of the high voltage power supply, which was in the millisecond range.

In the Soviet Union at that time one of the main tasks was to improve the accuracy of RLG. The goal was achieved by improving the gyroscope layout and associated electronics, changing to the glass/ceramic materials (pyroceram and so on.). Plant "Arsenal" with his central design bureau (CDB) was no exception. "Empty" (without any non-reciprocal elements) resonators were developed in Kiev in mid 80s for the need of navigation systems. Zero stability of 0.03 °/h was achieved by using traditional mechanical dither.

By the beginning of the 90s the *Arsenal* and CDB had diverse technologies allowing manufacturing RLGs of various modifications at their disposal. For example, a small series production of special triangular configuration RLG, which was the basis for the dynamic laser goniometer co-developed with Leningrad Electrotechnical Institute. This device have been widely used not only in the CIS but also abroad [18].

In the UK the laser gyro was again demonstrated in Farnborough in the early 80s. This time, the researches of two companies – British Aerospace and Ferranti – were demonstrated. Each presented its system based on RLG with perimeters of 30 and 43 cm, respectively. As a result, the government signed an agreement with each of the companies for 1 million £. Companies were required to submit 2 new SINS for aviation by January, 1986. It should be noted that the British Aerospace relied on the U.S. patents obtained by purchasing department of Sperry Gyroscope, while Ferranti was doing their own research [19].

RLG of the second generation

The beginning of the 1990s was marked by the collapse of the Soviet Union and the end of the Cold War. This led to a sharp decrease in funding for military research on both sides. So the civil market became essential. U.S. companies were actively reforming and absorbing each other. Nevertheless, existing and newly developed RLGs could already provide sustained release of products based on them: inertial modules, SINS, and integrated navigation system. Complete samples of control and navigation systems begin to appear in the market. Examples of these devices are shown in Fig. 11.

a) *b)* *c)* *d)*

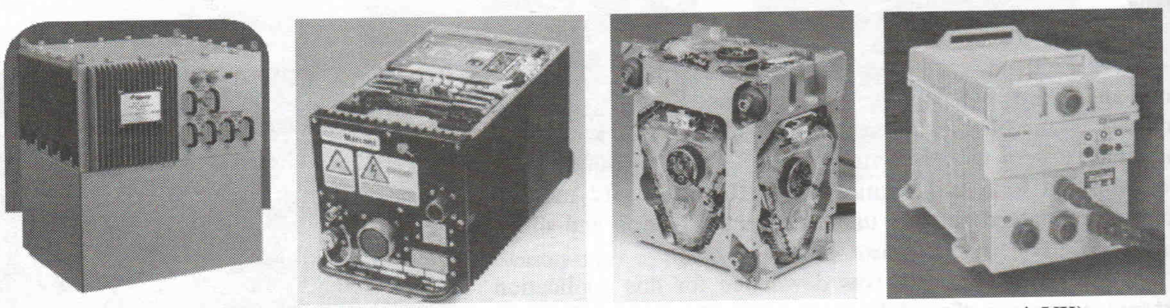


Fig. 11. Modern SINS: *a)* Marine INS MK-39 (Northrop Grumman, USA); *b)* FIN 3110 (Marconi, UK); *c)* the internal structure of FIN 3110; *d)* SIGMA 40 (Sagem, France)

Many of these systems are still relevant today. In particular, the INS SIGMA 40 is installed on vessels of 35 fleets in Europe. British system FIN 3110 (BAE Systems) is planned to be installed in mortar Agrab Mk .2 for the UAE Armed Forces in 2013 [20].

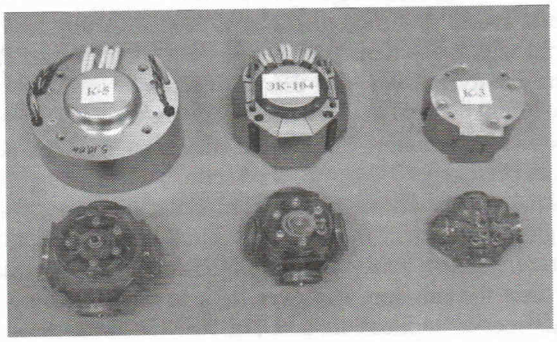


Fig. 12. Modern serial ZLG, produced by R&DI "Polyus"

In Russia, despite the difficult economic situation, the development of RLG continued in the direction of increasing the accuracy and the creation of integrated navigation systems and SINS. In 1990 – 1994 the development of new dual-mode and shock resistant RLGs is continued. The new RLG design concepts for ground moving objects, that solve the problems of gyrocompassing and current orientation, are being found. One of the biggest achievements of laser-gyro direction in 90s is the creation of integrated SINS NSI-2000 based on Zeeman ring laser gyros. Some examples of serial RLGs produced by R&DI "Polyus" are shown in Fig. 12.

Characteristics of the most commonly used modern foreign and domestic RLGs, as well as systems based on them, are presented in Tables 1–4.

Table 1

Modern US RLGs

Manufacturer	Honeywell			Northrop Grumman (Litton)		
Model	GG-1342	GG-1320	GG-1308	LG-2728	LG-2717	ZLG
Perimeter, cm	32	15	6.1	28	17	18
Weight, kg	1.9	-	0.2	1.5	1.5	-
Size, cm	15.7×14.7×5	-	-	14×17.7×5	14×11×6.5	-
Material	Cervit			Zerodur		
Biasing	Mechanical dither					4- frequency
Number of reflectors	3	3	3	4	4	4
Maximum angular rate. deg/s	800	500	1000	400	800	400
Bias instability (1-10 h), deg/h	0.007	0.002	1.0	0.005	0.02	-
Bias instability (run to run). deg/h	0.01	-	1.0	0.01	0.04	0.003
Angle random walk, deg/$\sqrt{h}$	0.003	0.0018	0.1	0.003	0.015	0.0015
Scale factor, arc. s/pulse	2	4	9	1.8	3.0	0.75
Scale factor stability	5×10^{-5}	1×10^{-5}	1.5×10^{-4}	5×10^{-6}	5×10^{-5}	2×10^{-7}
Temperature sensitivity of bias. (deg/h)/°C	0.002	-	-	-	-	0.002

Table 2

Modern SINS in USA and Europe

Manufacturer	Sagem			Northrop Grumman	Honeywell	Kearfott
Model	SIGMA 40	SIGMA 40 XP	SIGMA 95 N	MK-39	HG-1700	KI-4939
Application	Naval		Aviation	Naval	Missile	
	abovewater	underwater				
Size, mm	285×225×410		209×200×385	444×491×621	Volume of 541 cm^3	97×89
Weight, kg	24		<15	–	<0.9	0.9
Position accuracy, Nm/h	0.06	0.04	<0.5	0.125	–	–
Known consumers	Over 35 fleets in Europe, UAE, India and South Korea	–	France and other European countries Air Forces; export version of MiG-29 (“Fulcrun”)	NATO naval vessels	–	–

Table 3

Modern Russian RLGs

Manufacturer / Parameter	SIC "Elektrooptica"		R&DI "Polyus"	OJSC "MIEA"	OJSC «TEMP-AVIA»	OJSC «Ramenskii instrumentation factory»	
	GL-1	GL-2	MT-401	LG-2	LG-2	GL-1	LChE
Perimeter, cm	44	28	18	28	16	–	
Weight, kg	4	2	5.5	1.8	1.5	4	
Size, cm	∅20.6×10	15.4×11.6×9	∅18×14	145×130×47	–	∅206×105	∅176×166
Material	Pyroceram		Pyroceram	Pyroceram	–	–	–
Biasing	Mechanical dither		Zeeman bias	Mechanical dither	–	–	–
Number of reflectors	4	4	4	4	4	4	3×3
Discharge	HF discharge		DC	DC	–	–	–
Power, W	24 V/0.6 A	30 V/0.6 A	68	–	13	–	–
Maximum angular rate. deg/s	360	500	600	–	200	90	400
Bias instability (1-10 h), deg/h	0.07	0.01	0.5-1.0	0.01	0.4	0.05	–
Bias instability (run to run), deg/h	0.01	0.01	0.3	–	–	0.02	0.1
Angle random walk, deg/$\sqrt{h}$	0.003	0.005	–	–	–	–	–
Scale factor, arc. s/pulse	1.3	2.24	3.33	2.2	–	–	–
Scale factor inlinearity	5×10^{-6}	5×10^{-6}	2×10^{-4}	–	–	–	–
Scale factor stability	1×10^{-5}	1×10^{-6}	–	1×10^{-5}	7×10^{-5}	5×10^{-5}	5×10^{-5}
Temperature sensitivity of bias (deg/h)/°C	0.003	0.002	–	–	–	–	–

Table 4

Modern RLG-based SINS in Russia

Manufacturer	OJSC «TEMP-AVIA»		OJSC «Ramenskii instrumentation factory»			R&DI "Polyus"
Model	BChE-TKL	BINS-LG	BINS-SP	BINS-LChE	BChE-M40	AIS-402
Size, mm	–	–	190×198×400	190×190×340	100×100×120	∅18×240
Weight, kg	4.5	10	15	15	1.4	8.5
Maximum angular rate, deg/s	600	300	400	400	1000	600
Power, W	27	40	70	80	15	45
Pitch and roll error, deg	–	0.005	0.1	0.1	–	–
Yaw error, deg	–	1	$0.1+0.01t$	0.05	–	–

State-of-the-art of RLG-based IMU market

Today, manufacturers rarely supply separate RLGs to the market. Typically, the end product is the inertial measurement unit (IMU) or complete system. Let us study the IMU market in more details, relying on the research by Yole Développement [21]. Inertial Measurements Units are manufactured traditionally by an industry dominated by defense and aerospace applications. 2011 was a stable year for IMUs with a market size of $1.75 billion (Fig. 13).

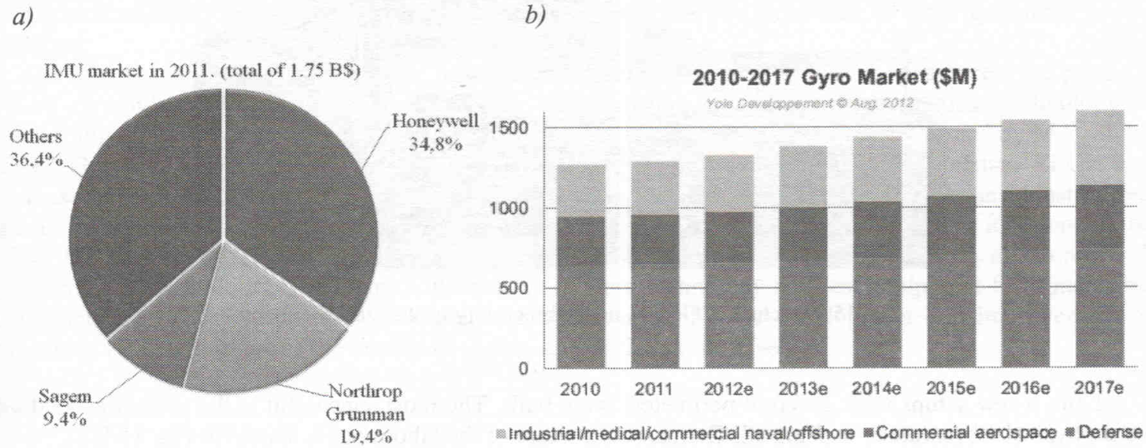


Fig. 13. Share of different manufacturers in the IMU market (*a*); the gyroscopes market in different years (*b*)

As can be seen from Fig. 13 (a), the IMU market is very concentrated; with only a few big companies being dominant. Honeywell, Northrop Grumman and Sagem are the clear leaders, but many newcomers are coming in to play, looking to enter the market with low-cost MEMS-based products and a different approach to how things are done.

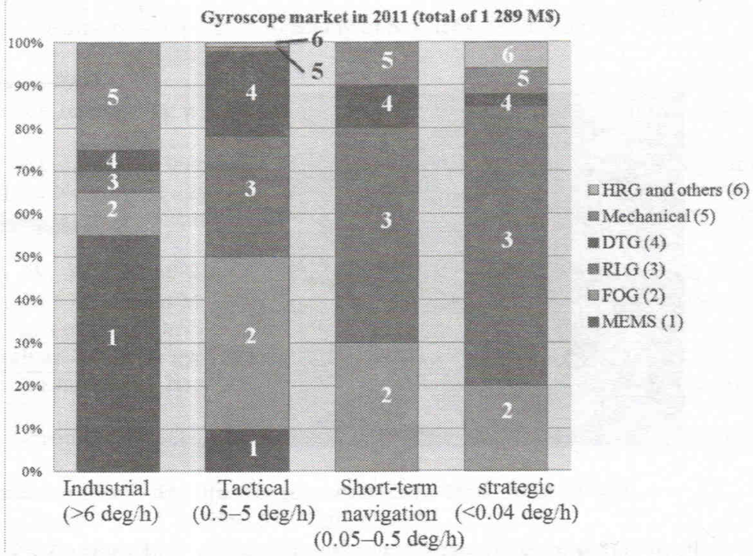


Fig. 14. Sales of different types of gyroscopes in 2011

High-performance inertial sensors and systems is a dynamic market segment, as an ever-increasing number of platforms require stabilization, guidance or navigation functions. The 2011 market for high-performance gyroscopes was estimated at $1.29 billion, growing at a 4.3% annual rate, and is expected to reach $1.66 billion in 2017. (Fig. 13 (b)). It should be noted that much of this growth is achieved by popular FOG and MEMS gyroscopes, which year after year improve their performance. In order to determine the place of RLG among all variety of sensors on the market, let us consider the histogram in Fig. 14.

Currently, the optical gyroscope still dominates the market by a wide margin. In particular, RLGs are largely used in navigation systems and tactical guidance. With increasing accuracy the RLG's share increases significantly. If in low precision sensors MEMS sensors are dominant due to their low cost and small size, then in the area of strategic navigation RLG share is over 60%.

Ultra large ring laser gyros

Despite the fact that a lot of gyroscope scientist efforts involve reducing the size of the sensors, there is an opposite direction – the development and construction of ultra large RLGs that opened completely new areas of its implication.

In the mid-80s a group of scientists from the University of Canterbury (Christchurch, New Zealand) was engaged in the development of the laser gyro that can detect a variety of effects that appear in the Earth's rotation. To achieve the required sensitivity values, it was decided to increase the perimeter of the cavity over conventional gyroscopes. The first example of such a sensor was constructed by 1989. It was called C - I and had a square cavity with a side of 85 cm. It was able to measure the speed of the Earth rotation, and also showed the possibility of building a RLG with a large perimeter.

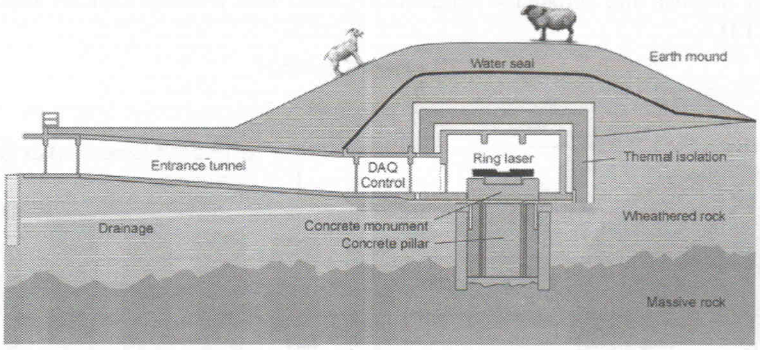


Fig. 15. Structure of Geophysical Observatory in Wettzell, Germany

Later a few setups with different perimeters were built. The most successful is the project carried out at the Geophysical Observatory in Wettzell, Germany. Structure of the laboratory is shown in Fig. 15 [22].

The gyro made of Zerodur has a square resonator with a side of 4 m. Structural assembly (fig. 16, *a*) is placed on a massive concrete base to a depth of several meters underground.

a) *б)*

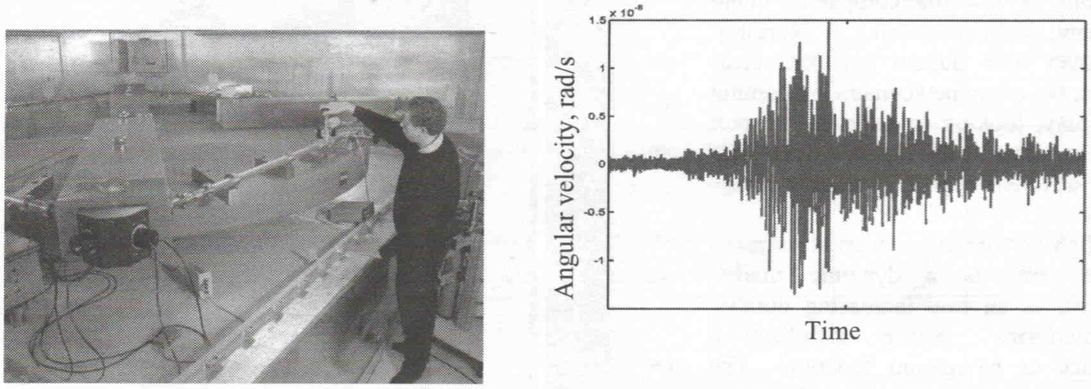


Fig. 16. Ultra-large RLG "Grossring G" (*a*); gyro signal from a faraway earthquake (*b*) (Algeria, 21.05.2003)

In the laboratory all steps have been taken to avoid spurious effects of external factors on RLG. As a result there is an superprecision apparatus that is capable to measure the Earth rotation with a great resolution. It can provide the data about the Earth axis daily oscillations (~ 24 hour period, the amplitude of 5-60 cm), the Chandler wobble (period 433 days, the amplitude of ~ 9 m), tidal fluctuations. A special role is played by the device of this kind in seismology. Due to the high sensitivity, large laser gyros can capture signals from distant earthquakes (Fig. 16, *b*).

Today there are a number of such devices located in different countries and pursuing different aims: the detection of seismic activity, the study of the Earth, the assessment of building supports vibrations, detecting small shifts in the design of the gravity waves detector, etc. The most ambitious is now the gyroscope UG -2, located in Kashmir cave laboratory (New Zealand). Perimeter of the gyroscope is 39.7 x 21 m. This project aims to assess the possibility of further laser gyroscopes perimeter increasing. According to researchers, these model have shown that the scale factor instability is growing much faster than the sensitivity while increasing the size.

Conclusions

In 1962 RLG with its appearance not only opened a new era of wave gyroscopes, but also created the conditions for the rapid development of the strapdown inertial and, in consequence, integrated navigation systems. For 50 years, scientists around the world have worked hard to ensure that we can now state with certainty: "A laser gyroscope is a key element in modern navigation, orientation and stabilization systems". Unfortunately, a short report could not contain all the scientists and companies involved in the development of RLG, so the work mention the ones were information was available in open sources.

For many years, the ring laser gyro held the title of "critical technologies". Some of the market review shown demonstrated that, despite active competition with FOG and micromechanical gyroscopes, RLG retained leading positions in high-end SINS. The forecast made by Academician V.G. Peshekhonov in [1]: "High- and mid-precision SINS will be based on optical wave gyroscopes and produced in large quantities", – is fully justified.

Ring laser gyroscopes justly are among the most high-tech and unique laser devices, the production of which accumulates and stimulates the development of emerging technologies including nanotechnology. Today, the leading domestic company in the field of ring laser gyroscope is "R&DI "Polyus" named by M.F. Stelmakh". Yu.D. Golyaev, who is the leader of CPP-470 responsible for the development of Zeeman RLGs, noted an increase in both RLG demand and volume of its production. Existing gaps in the Russian industrial base are gradually eliminated. This process can be accelerated by attracting foreign technologies, as it is done in the field of MEMS or in the automotive industry. Today the companies are bringing together optical, electronic, and other industries and provide RLG industry with the best modern technology and test equipment for a major base re-manufacturing. These steps and the available scientific basis for the development and improvement of new models of RLG will improve the quality of instruments and systems based on them.

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