Research on Principle, Application and Development Trend of Laser Gyro

Shaodi Wang\textsuperscript{a}, Zhili Zhang\textsuperscript{b}
Rocket Force University of Engineering, Xi'an 710025, China
\textsuperscript{a}247717287@qq.com, \textsuperscript{b}157918018@qq.com

Abstract. The paper briefly introduces the working principle, main structure and function of the laser gyro, and expounds its advantages over other gyros. At the same time, the paper combs the development history of laser gyro and the application of foreign manufacturers' products, and analyses the main methods and future development trends to improve its accuracy.

1. Introduction
In recent years, such as Iraq, Libya, Syria and other local wars, the weapon system and its launching platform have used a large number of inertial guidance or inertial navigation systems. Laser gyros as an important component of inertial guidance, overcoming the spin gyro and vibrating gyro, overcoming The factors affecting the accuracy of the gyro, such as acceleration and gravity effects, have the advantages of high precision, large dynamic range, fast starting speed, good scale factor, strong environmental adaptability, high reliability and long working life. Laser gyro and its inertial navigation system are not only applied to a variety of precision strike weapons, but also have a wide range of applications in aerospace, satellite communications, oil exploration, marine monitoring and other fields [1-3]. For a long time, Western countries have been exporting embargoes to China in the field of high-precision laser gyros and other inertial instruments. In order to break the foreign technology blockade, further research on inertial instruments such as laser gyros is needed.

2. Laser gyro principle
Laser gyro is the product of modern physics in the electromagnetic theory and quantum mechanics of light, the laser and modern technology revolution, mainly applied the Sagnac effect and laser technology, is a new type of medium and high precision optical inertial instrument.

2.1. Sagnac effect
In 1913, the French scientist Sagnac discovered and proposed the Sagnac effect when studying the rotating annular optical interferometer. The Sagnac effect mainly occurs in the ring-shaped optical path, which may be triangular, quadrangular, polygonal or circular [4-6].
Take the ring light path in an ideal vacuum environment as an example. As shown in Fig. 1, in the annular optical path with radius \( R \), two beams of light are simultaneously emitted from the position of the beam splitter \( M \), and two beams of light in the clockwise and counterclockwise directions are independently advanced. When the annular optical path is not relative to the inertia space, when rotating, the optical path lengths in the forward and counterclockwise directions are the same, and \( c \) represents the speed of light in the vacuum. When the optical path \( 2\pi R \) experienced passes the time \( t = 2\pi R/c \), the two beams of light return to the beam splitter \( M \) at the same time. At this time, the phase difference of the beam is zero.

However, when this annular optical path is rotated at an angular velocity \( \Omega \) relative to the inertial space, the optical path symmetry will no longer exist. The smooth and counterclockwise path will produce a difference. Assuming that the annular closed optical path rotates in a clockwise direction, the beam propagating in the counterclockwise direction reaches the beam splitter again after one round of the annular optical path, and the position of the beam splitter will appear at \( M' \), and the beam propagating counterclockwise will propagate for one week. The optical path is shorter than the circumference of the annular optical path, and the optical path in the clockwise direction is longer than the circumference of the annular optical path, and the size is

\[
L_{\text{inverse}} = 2\pi R - R\Omega t_{\text{inverse}} \tag{1}
\]

\[
L_{\text{along}} = 2\pi R + R\Omega t_{\text{along}} \tag{2}
\]

The time difference between the two beams is

\[
\Delta t = t_{\text{along}} - t_{\text{inverse}} = R\Omega t_{\text{along}} - t_{\text{inverse}} / c \tag{3}
\]

Combined with formula (1) and formula (2)

\[
(t_{\text{inverse}} + t_{\text{along}})\left[4\pi R + R\Omega(t_{\text{along}} - t_{\text{inverse}})\right] / c = (4\pi R + R\Omega \Delta t) / c \tag{4}
\]

Substituting equation (4) into equation (3), when \( 4\pi R \) is much larger than \( R\Omega \Delta t \), it is available.

\[
\Delta t = R\Omega(4\pi R + R\Omega \Delta t) / c^2 = 4\pi R^2 \Omega / c^2 \tag{5}
\]

When the area of the annular optical path is \( S = \pi R^2 \), the phase difference of the Sagnac effect caused by the rotation when the two beams of light propagate in opposite directions is

\[
\Delta \phi = \omega \Delta t = 4\sigma R \cdot S / c^2 = 8\pi R \cdot S / (\lambda c) \tag{6}
\]
Figure 2. The Sagnac effect in an arbitrary ring path.

As shown in FIG. 2, when an arbitrary shape of the closed optical path is rotated in any axial direction, the optical splitter is used to couple the optical light into an arbitrarily shaped closed optical path, and the two beams of light propagate in a smooth, counterclockwise direction in the optical path. A small piece of line element along the direction of light propagation at any point on the closed optical path can be expressed as

\[ dl = l dl \] (7)

Where: \( l \) is the tangential unit vector of the line element.

If the closed optical path is rotated at an angular velocity \( \Omega \) around a certain axis, the linear velocity \( v \) of the line element in the closed optical path is

\[ v = \Omega \times r \] (8)

Where: \( r \) is the radial coordinate vector of the rotating shaft to any point of the closed optical path.

The linear velocity component induced in the \( l \) direction can be expressed as \( v \cdot l \) when the closed optical path is rotated. The beam propagating in the direction of rotation, taking into account \( c \), \( v \cdot l \), the time elapsed through line element \( E \) is

\[ dt_+ = dl / c + v \cdot l dl / c^2 \] (9)

According to the light path, the integral of formula (9) is available.

\[ t_+ = \int dt_+ = \int (dl/c + v \cdot l dl/c^2) = L/c + \frac{\Omega \times r}{c^2} l dl = L/c + \frac{1}{c^2} \mathbf{\nabla} \times (\Omega \times r) \cdot dS \] (10)

Using the formula of rotation in equation (10)

\[ \nabla \times (\Omega \times r) = \Omega (\nabla \cdot r) - r(\nabla \cdot \Omega) + (r \cdot \nabla) \Omega - (\Omega \cdot \nabla) r \] (11)

When \( \nabla \cdot r = 0 \), there is no spatial dependence on the speed \( \Omega \), and the fourth item on the right side of the equation (11) can be expanded.

\[ (\Omega \cdot \nabla) r = (\Omega_x \partial_x + \Omega_y \partial_y + \Omega_z \partial_z)(x \partial x + y \partial y + z \partial z) = (\Omega \cdot x + \Omega_y \cdot y + \Omega_z \cdot z) = \Omega \] (12)
Substitution (10) is reduced to

\[ t_+ = \frac{L}{c} + \frac{1}{c^2} \oint \mathbf{V} \times (\mathbf{\Omega} \times \mathbf{r}) \cdot d\mathbf{S} = \frac{L}{c} - 2\mathbf{\Omega} \cdot \mathbf{S} / c^2 \]  \hspace{1cm} (13)

Similarly, the beam travel time in the opposite direction is

\[ t_- = \frac{L}{c} - 2\mathbf{\Omega} \cdot \mathbf{S} / c^2 \]  \hspace{1cm} (14)

By using the propagation time difference of the two beams propagating in the forward and reverse directions, the phase difference of the Sagnac effect of the two beams can be obtained when the optical path of any closed shape is rotated.

\[ \Delta \phi = \omega \Delta t = 4\omega \mathbf{\Omega} \cdot \mathbf{S} / c^2 = 8\pi \mathbf{\Omega} \cdot \mathbf{S} / (\lambda c) \]  \hspace{1cm} (15)

The phase difference of the Sagnac effect of the two beams, the equivalent area \( S \) of the closed optical path perpendicular to the axis of rotation (equal to the product of the circumference of the closed path and its average radius) and the rotational speed of the closed path are proportional to the axis of rotation. The position and the shape of the closed light path are irrelevant. Therefore, for a closed optical path of any shape, as long as the change or phase difference of the interference fringes of the two beams in the forward and counterclockwise directions is measured, the angular velocity of the closed optical path rotating around the arbitrary rotational axis in the inertial space can be obtained.

2.2. Laser

The ring laser is the basis of the laser gyro. It is the Sagnac effect generated by the two coherent lasers with positive and negative polarization in the ring laser that can sense the angular velocity of the carrier [7-8].

2.2.1. Stimulated radiation. Unlike ordinary visible light, laser is a special kind of light. In 1917, on the basis of quantum physics, Albert Einstein proposed the concept of stimulated radiation, that is, the phenomenon of matter luminescence is the result of the interaction between particles and radiation field. A certain number of particles at the same high energy level E2, when the incident photon interacts with the first particle to cause the particle to transition to the low energy level E1 and produce a photon of the same characteristic, thereby obtaining two photons having the same characteristics, the two The photon interacts with the other two particles to produce four photons. According to this law, a series of photons are obtained. These photons are at the same frequency, in phase, in the same direction of propagation, and in the same polarization as the incident photons. A device that supplies energy from the outside to these excited state particles is referred to as a "pump source." When the substance is in thermal equilibrium, its internal particles are distributed at various energy levels. The number of low-level particles is much larger than the number of high-energy particles. Photons generated in the material are gradually absorbed by low-level particles, and lasers cannot be generated. When the “pump source” supplies energy to the material to break the thermal equilibrium state, the number of particles in the material at the high energy level E2 will be greater than the number of particles in the low energy level E1, and the number of particles will be reversed, and the incident photons interact with the particles to produce more and more The characteristic photons also produce laser light.

2.2.2. Optical cavity. The gain medium in the optical cavity of the ring laser is the working substance of the laser. When the external energy is supplied, the atoms or molecules in the gain medium are
inverted by the number of particles, so that the particles are stimulated to obtain light amplification. When the optical cavity starts to work, there are fewer photons generated in the gain medium. Most of the particles in the high energy level are not excited. A positive feedback mechanism is needed to participate in the optical amplification. The system composed of the surface mirrors in the cavity can the photons along the axis are reflected back into the gain medium, exciting to generate more photons, forming a self-oscillation on the axial optical mode, and non-axis photons will be reflected out of the system. The optical cavity mainly has two functions: one is to select a specific mode of laser, that is, the laser that only retains a specific eigenstate undergoes self-oscillation after multiple reflections, and improves the coherence of the output laser. The second is to provide feedback so that the intracavity laser traveling wave propagates through the mirror enough back and forth to form a stable field distribution, that is, the field distribution when the "self-reproducing" laser starts. When the geometric parameters such as the cavity length of the cavity change, the frequency of the laser in the cavity will also change.

In a ring laser, the frequency of the traveling wave of the laser oscillating clockwise and counterclockwise is related to the forward and reverse closed cavity length of the annular cavity, where \( q \) is a positive integer.

\[
\begin{align*}
\nu_{\text{inverse}} &= \frac{qc}{L_{\text{along}}} \\
\nu_{\text{inverse}} &= \frac{qc}{L_{\text{inverse}}}
\end{align*}
\]  

When the ring laser rotates at the angular velocity \( \Omega \), the forward and reverse cavity length difference \( \Delta L = L_{\text{along}} - L_{\text{inverse}} \) is converted into a smooth and counterclockwise laser oscillation frequency difference.

\[
\Delta \nu = \nu_{\text{along}} - \nu_{\text{inverse}} = \nu \Delta L / L = 4S \cdot \Omega / (\lambda L)
\]

Equation (17) shows the principle of the laser gyro. As long as the frequency difference between the forward and reverse laser traveling waves is measured, the rotational angular velocity can be obtained, and the rotational direction of the ring laser can be determined according to the positive and negative frequency differences.

3. Laser gyro structure

The main components of a typical machine shake laser gyro include: ring laser, frequency offset component, frequency stabilization component length control component, logic circuit, signal readout system, electromagnetic shield and power supply components and installation structure. The core component of the laser gyro is a ring laser, which is the decisive component of the performance of the laser gyro. The laser ring resonator is generally made of ceramic glass (also called glass-ceramic) material with a small coefficient of thermal expansion. Other components belonging to the control system are mainly used for precision control, error compensation and data readout [3].

As shown in FIG. 3, the laser gyro includes a cathode, a common anode, and a pumping anode, which are electrodes for discharging a gas in the resonant cavity; under the excitation of the high voltage power source, the krypton mixed gas generates a glow discharge. The high-energy electrons generated by the glow discharge cause the helium atom to be excited to a high-energy level, and the high-energy helium atom is excited by the resonance transfer to transfer the energy to the ground-state helium atom, and the energy-transferring helium atom excites the helium atom to a high-energy state. Thereby, stimulated radiation is generated between certain high and low energy levels of the helium atom, and laser light is generated in all directions. The mirror is placed at three vertex positions of the helium atom, and the geometric position of the mirror is guaranteed to be the same along the three center lines. The laser can be repeatedly operated in the annular optical path. At the same time,
the laser gain medium, that is, the working gas, provides an excited transition to maintain the traveling wave oscillating light field in the cavity, that is, a laser beam with a relatively stable clockwise rotation and counterclockwise rotation. The advantages of using He-Ne laser are: good monochromaticity, narrow spectral line width, up to 103 Hz, small divergence angle, stable output power and stable frequency.

The dithering circuit of the laser gyro generates a fixed-frequency sine wave whose amplitude changes according to a certain law, and the frequency is equal to the frequency of the gyro itself, so that the piezoelectric ceramic component on the vibrating wheel works to generate jitter. A pair of lasers traveling waves emitted from the primary reflection sheet are combined into the same direction by the reading prism, and the angle can be angled. The pair of lasers traveling waves are substantially equal in intensity after being combined by the translatve film to form interference fringes. The photoelectric reading device can detect the intensity variation of the interference fringes, and obtain the rotational angular velocity $\Omega$ by directly measuring the light stripe information.

**Figure 3.** Schematic diagram of a typical machine shake ring laser gyro.

4. Development history and application of laser gyro

4.1. Development history

In 1897, British physicist Oliver Lodge first proposed the concept of optical gyro. In 1913, the French scientist Sagnac proposed the famous Sagnac effect. Because there is no suitable coherent light source, the research progress is slow and there is basically no practical product. In 1960, after American scientist T. H. Maiman invented the world's first laser, the ruby solid-state laser, the laser gyro based on the Sagnac effect became a research hotspot. In 1961, the American scientist Heer C. V. proposed for the first time to measure the change of the angular rate of the external input by measuring the Sagnac effect in the ring laser cavity. In 1962, the United States, Britain, France, the former Soviet Union and other countries began to work on the development of laser gyros. In February 1963, Sperry developed the world's first ring laser gyro with a square light path length of 1 m and a wavelength of 0.663 to measure the rotation rate. In the subsequent development process, the latching effect of the laser gyro, the zero-offset error, and the manufacturing process problems such as air leakage, packaging, and coating were solved one by one. In 1972, Honeywell developed the first mechanically graded GG1300 single-axis laser gyro, which was successfully used on aircraft and missiles. The laser gyro began to enter the practical stage. Since the 1980s, laser gyros have gradually replaced mechanical gyros, which are widely used in various types of aircraft, ships, submarines, missiles,
launch vehicles, industrial robots and other navigation systems. In 1994, after the United States and Russia, China became the fourth country in the world to independently develop and produce laser gyro. Although China’s research on laser gyro technology started later than other developed countries, with the hard work of many scientific researchers, China built a complete closed-loop high-tech laser gyro R&D system with independent intellectual property rights in 2014, reaching the international advanced level.

At present, the key technologies in the field of laser gyro are mainly controlled by the United States, Japan, Germany, France, Russia and other countries, including the US DARPA, Draper Lab, Northrop Grumman, Honeywell, and Kilford (Singer-Kearfott); France Safran Electronics and Defense Company, Sextant; Japan’s Space Development Group (NASDA), Japan aviation Electronics industry Limited (JAE), National Aerospace Laboratory; Russia’s Polyus Institute, Electro-optical (Electrooptika) company, etc. [9-12].

4.2. Development trend of laser gyro
After years of development, laser gyro technology has been widely used. Further improvement of accuracy and reliability, cost reduction and miniaturization are inevitable requirements for future development. There are two main problems to improve the accuracy of laser gyro: one is to improve the precision of cavity machining process, the precision machining and optical processing technology in glass, the high-precision polishing on ultra-smooth surface and the low-loss anti-damage coating technology, high precision. Research on key process technologies such as assembly and error control technology; secondly, errors such as latch-up, zero drift, and scale factor variation in the laser gyro are still the main factors restricting their development. In order to reduce the influence of the lock zone, the frequency offset technique can be used, that is, adding a frequency offset to make the gyro workspace cross the lock zone. Currently, the mechanical jitter bias frequency, the magneto-optic effect bias frequency, the rate offset frequency and the four-frequency difference are mainly used. Mobility method [13-14].

In order to eliminate the jittery off-frequency laser gyro in the inherent lock zone, the artificially applied angular vibration by mechanical force or interference force will cause the laser gyro to lose the "solid state" characteristic, and the output signal will generate demodulation error due to the removal of the angular vibration, resulting in increased noise. Bring random walk error. At present, the research focus is still on the new generation of non-coplanar four-frequency differential laser gyro (FMDLG) with no mechanical jitter, which eliminates the influence of noise, and the linearity of the scale factor is high. It is more suitable for the application of special requirements for noise and large dynamic mechanical environment. The next problem to be solved is to reduce its temperature sensitivity and magnetic field sensitivity, and to ensure the stability of the output zero bias. The zero drift of the laser gyro is mainly reflected in the instability of the zero offset. The error sources include the anisotropy of the refractive index of the optical path in the cavity and the temperature change. As the external high and low temperature changes, the output bias will be affected by temperature changes, affecting the accuracy of the gyro. There are two main research directions for suppressing temperature error: one is to improve the design, material and process level, to improve the structure and component performance of the gyro; the other is to find and establish a mathematical model of temperature and zero bias to study and improve the temperature stability of the gyro. Compensation method. For the navigation system composed of the four-frequency laser gyro, strict magnetic shielding, stability control measures and automatic modulation technology of rotational modulation can be adopted to further eliminate the constant value drift and slow drift. At the same time, combined with a variety of sensors such as GPS, synthetic aperture radar for information navigation, and further improve the navigation accuracy of the laser gyro inertial system is also one of the focus of the next research.
5. Conclusion

With the development of inertial technology and its new devices, laser gyro inertial navigation systems have been widely used in various fields such as sea, land, air, and sky, although high precision such as fiber optic gyroscopes, hemispherical resonator gyroscopes, and micromachined gyroscopes have emerged. The new gyro, but the laser gyro still maintains the highest market share. In medium-precision applications where the stability of the calibration factor is extremely high, the zero-lock zone laser gyro is still the first choice. The overall cost performance and environmental adaptability are still in the actual environment. Leading position will still play a huge role in various fields. In the past 20 years, China has made a lot of fruitful work in the field of laser gyro from theory and practice. In the future, we need to further narrow the gap with other technology powers, and develop and promote our own top laser gyro inertial navigation products.

References

[1] Zhang Bin, Luo Hui, Yuan Baolun. Development and Application of Laser Gyro in Foreign Countries. Foreign Inertial Technology Information, 10 (4) (2017) 2-15.
[2] Yue Mingqiao, Wang Tianquan. Analysis and Development Direction of Laser Gyroscope. Flying Missile, 20 (12) (2005) 46-48.
[3] Luo Hui. Laser Gyro and Its Inertial Navigation System. Urban & Civilian Technology, 3 (11) (2015) 14-19.
[4] Lu Zhidong. Non-coplanar laser gyro. Beijing: Aviation Industry Press, 5 (7) (2014) 2-15.
[5] Bian Ting. Experimental study on accelerated life of annular cavity gas (He-Ne) laser. Xi’an: Xi’an University of Electronic Science and Technology, 3(14) (2010) 44-49.
[6] Wei Guo. Study on some key technologies of two-frequency machine-shake laser gyro two-axis rotary inertial navigation system. Changsha: National University of Defense Technology, 15(5) (2013) 13-19.
[7] Sheng Xinzhi, Yan Shuqin. Laser Principle. Beijing: Tsinghua University Press, 4(3) (2015) 4-9.
[8] Zhou Bingzhen, Gao Yizhi, Chen Yu, et al. Laser principle. Beijing: National Defense Industry Press, 11(7) (2014) 26-27.
[9] Xue Lianli, Chen Shaochun, Chen Xiaozhen. Development and Review of Foreign Inertial Technology in 2017. Navigation and Control, 17(2) (2018) 1-9-40.
[10] Fan Qiuli. Development and Application of Inertial Technology in Aviation Field. Aeronautical Missile, 18(10) (2017) 1-6.
[11] YANG Yefei, SHEN Wentao. Development Status and Application Research of Gyro Technology in Inertial Stabilization Platform. Control and Guidance, 7(2) (2011) 73-74.
[12] Li Decheng, Lin Size. Application of laser gyro technology in the field of inertial navigation. Proceedings of the Symposium on High-precision Geometric Measurement and Calibration Technology for 2008, 17 (11) (2008) 13-19.
[13] Yuan Wencheng, Han Lianyang, Guo Tong et al. Key Technologies of High Precision Laser Gyro. Weapons Development, 3(11) (2008) 3-5.
[14] Zeng Qinghua, Liu Jianye, Lai Jizhou, Xiong Zhi. The Latest Development of Ring Laser Gyro. Sensor Technology, 11(23) (2014) 1-4.