Chapter

On the Development and Application of FOG

Xuejuan Lin, Wenlong Han, Ke Chen and Wen Zhang

Abstract

Gyroscope is a type of angular velocity measuring device, which can precisely determine the orientation of moving objects. It was first employed in navigation and later became an inertial navigation instrument widely used in modern aviation, aerospace, and national defense industries. As a vital representative of gyroscope, the fiber-optic gyroscope (FOG) has advantages in terms of compact structure, high precision, high sensitivity, and high environmental adaptability. FOG has been broadly utilized in many fields, and is also a key component of modern navigation instruments. In this paper, the history, classification, performance indicators, and application requirements of gyroscope are briefly summarized. The development history of FOG based on Sagnac effect is described in detail. The three generations of FOG are interferometric FOG, resonant FOG, and stimulated Brillouin scattering FOG. At the same time, this chapter summarizes the development and research situation of FOG in the United States, Japan, France, and other major developing countries, and compares the application of FOG in various international companies.

Keywords: gyroscope, fiber-optic gyroscope, navigation, survey

1. Gyroscope

1.1 Development of gyroscope

At the beginning of the eighteenth century, human beings discovered that the rigid body with fast rotation has fixed axis and precession. Nowadays, gyroscope is generally used to measure angular velocity and displacement in relative inertial space. In 1765, Leonhard Euler, a Russian mathematician and physicist, published the article "The Theory of Rigid Body Moving around Fixed Point," and established the basic mechanics theory of Rotor Gyroscope. Then, the dynamic equation of rigid body rotation was deduced, which laid a solid foundation for the study of gyroscope theory. In 1778, Lagrange, a French scientist, established the differential equations of motion of a rigid body rotating at a fixed point under the action of gravitational moment in his book "Analytical Mechanics." In 1852, French physicist Foucault, based on the theory of rigid body motion put forward by predecessors, combined with his in-depth study of rigid body, first discovered that the rotor rotating at high speed in the middle of the earth always pointed to a fixed direction because of inertia, and created a measuring device for verifying the rotation of the earth [1], which was named as Gyroscope. This creates a precedent for the research and development of engineering practical gyroscopes [2]. H. Anschutz and Sperry produced Gyrocompasses which were mainly applied in navigation for ships at sea [1] in 1908 and 1909. The emergence of gyrocompass marks the formation of gyroscope technology and the opening of its modern application, which pushes the theoretical research of gyroscope to practical application.

1.2 Classification of gyroscope

According to the working principle of gyroscope, it can be divided into classical mechanics-based gyroscope and modern physics-based gyroscope.

Based on the different medium of angular velocity of sensitive carrier relative to inertial space, gyroscopes can be categorized into rotor gyroscopes, optical gyroscopes, magnetohydrodynamic gyroscopes, and atomic gyroscopes in engineering. The most common rotor gyroscopes include liquid-floated gyroscopes, dynamically tuned gyroscopes, electrostatic gyroscopes, and vibration gyroscopes. Optical gyroscopes include laser gyroscopes, fiber-optic gyroscopes, and micromachined gyroscopes include MEMS gyroscopes that have been applied in engineering [3].

1.3 Performance indicators and application requirements of gyroscope

In order to analyze and evaluate the overall performance of gyroscope, a series of criteria should be formulated to provide reference for its application. Generally speaking, the main indicators of gyroscope performance are scale factor

Performance indicator	Strategic level	Inertial navigation level	Tactical level	Commercial level
Scale factor stability/ppm	<1	1–100	100–1000	>1000
Drift stability/(°)·h^{-1}	<0.01	0.01–0.15	0.15–15	>15
Random walk/(°)·h^{-1}	<0.01	0.01–0.05	0.05–0.5	>0.5
Range/(°)·s^{-1}	>500	>500	>400	50~1000
Cost/$	20,000	10,000	1000	500

Table 1.
The classification of performance indicator in gyroscope.

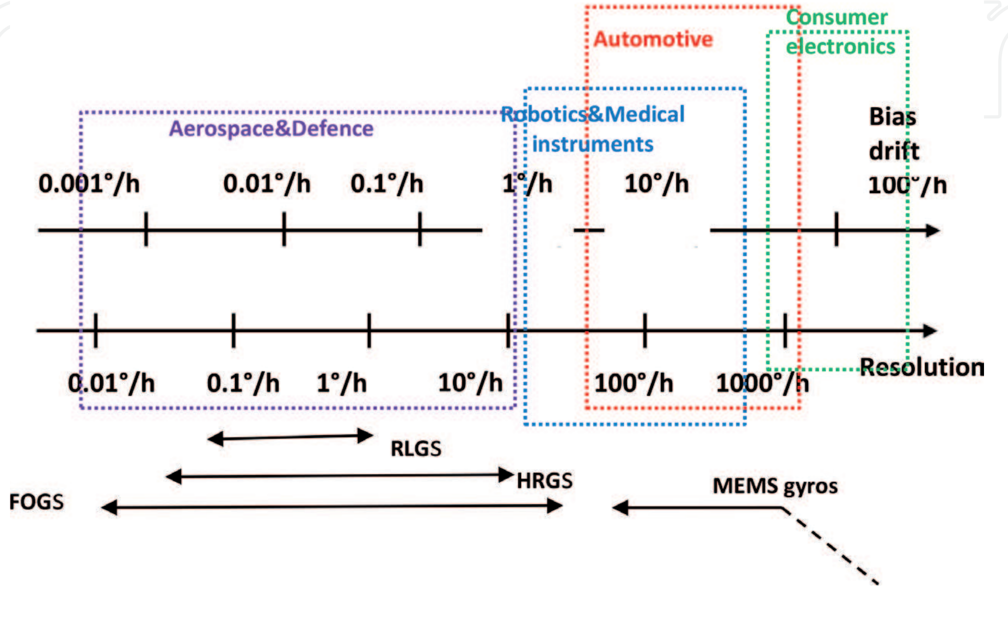


Figure 1.
The application requirements of different FOGs.

stability, drift stability, random walk, range and cost, etc. According to these indicators, gyroscopes are divided into four categories: strategic level, inertial navigation level, tactical level, and commercial level, as shown in **Table 1** [3].

Figure 1 presents the applications and requirements of different gyroscope technologies. Almost half of the high-performance gyroscope market is covered by national defense applications, while commercial aviation accounts for 25% of the market. At present, there are mainly two mature optoelectronic technologies in these two market areas, namely ring laser gyroscope (RLG) based on Sagnac effect [4] and fiber-optic gyroscopes (FOG) [5].

2. Fiber-optic gyroscope

In the 1970s, FOG was first proposed and studied [6]. Then, its emergence has opened the way for the research of all solid-state sensors. It was initially considered to be devoted to medium-level applications. But over time, it has made a number of outstanding achievements in theoretical research and engineering [7]. Nowadays, FOG has reached the strategic level of performance and surpassed the ring laser gyroscope in terms of deviation noise and long-term stability. Its advantages are becoming more obvious, and its application fields are becoming more extensive. It has gradually become the key development goal for each country.

2.1 Development history of FOG

In 1913, French physicist G. Sagnac presented a new theory through a considerable amount of experiments. The phase shift of two beams propagating along the closed optical path is proportional to the normal input angular rate of the closed optical path. That is the Sagnac effect [8]. Successful application of inertial navigation technology during World War II made FOG more challenging. In the early inertial navigation system, the sensor system used stable platform. With the progress of science and technology and the emergence of artificial satellite, people put forward the concept of strapdown inertial navigation, which has the characteristics of simple structure, small size, light weight, low cost, and easy maintenance. Sensitive devices are becoming more and more demanding. After World War II, gyroscopic technology has developed rapidly. In 1963, SePoy Gyroscope Company made a breakthrough in the area of optical gyroscope. The first experiment demonstrated ring laser gyroscope. Thereafter, after nearly 20 years of efforts, the inertial ring laser gyroscope has become practical. In 1983, Honeywell's ring laser gyroscope was installed in the airborne strapdown inertial navigation system of the new passenger aircraft Boeing 767 and 757. The rapid development of optical fiber communication, fiber optics, and laser technology has promoted the further development of optical rotation sensor based on Sagnac interferometer. In the mid- and late 1970s, a new type of optical gyroscope, named fiber optic gyroscope, appeared.

Scientists Macek and Davis confirmed the correctness and realizability of ring laser gyroscopes in 1963. In 1967, the French physicists G. Pincher and G. Herpner proposed the hypothesis of using optical fibers in gyroscopes [4]. In 1976, American scientists Victor Vali and Richard W. Shorthill tested the hypothesis of G. Pincher and G. Herpner, which symbolized the transition from theoretical stage to practical stage of FOG [9]. In 1978, McDonald Company developed the first practical FOG, and in 1980 Bergh et al. produced the first all-fiber optic gyroscope test prototype, making FOG a big step toward practicality [10]. In the mid-1980s, the interferometric fiber optic gyroscope was successfully developed. The development and application of optical gyroscope is an important milestone in the history of inertial navigation technology. FOG has great value in the military field, because of its remarkable advantages, flexible structure, and broad application prospects. It has attracted the attention of universities and scientific research institutions in many countries in the world, and has invested a lot of energy in research. At the end of 1980s and the beginning of 1990s, FOG technology has been widely used. Its sensitivity has been improved by four orders of magnitude, and the angular velocity measurement accuracy has been improved from the initial 15°/h to 0.001°/h.

2.2 Classification of FOG

The development of FOG can be roughly divided into three generations: interferometric FOG, resonant FOG, and stimulated Brillouin scattering FOG [11], as shown in **Table 2**.

2.3 Basic composition of FOG

FOG is based on solid-state technology of optical fiber communication. Specifically, the main components of FOG are shown in **Figure 2** [15]:

1. AAA, an advanced broadband source based on EDFA technology, has a wavelength of 1550 nm. Wavelength stability can be obtained by internal spectral filtering with fiber Bragg grating.

2. Polarization-maintaining optical fiber coils (hundreds of meters in mid-range and kilometers in high-grade).

3. The integrated optical circuit of Linbo3 with electrodes is used to generate phase modulation and provide good polarization selectivity through proton exchange waveguide.

4. An optical fiber coupler (or circulator for higher return power) for transmitting signals to the detector light returned from the common input-output port of the interferometer.

5. Analog-to-digital (A/D) converter for sampling detector signals.

6. The digital logic electronic device that generates phase modulation and phase feedback through a digital-to-analog converter.

Note that with proper design and components, FOG performance is repeatable in production, even for high-performance terminals.

2.4 Principle of FOG

2.4.1 Interferometric FOG

When the whole system rotates, two beams of light propagating in the opposite direction produce phase difference, and the interference intensity changes. Interferometric FOG can calculate the rotation angular velocity according to the intensity change detected by the optical detector.

The light emitted by the light source is divided into two identical beams through the beam splitter, which propagate in a closed optical path counterclockwise and

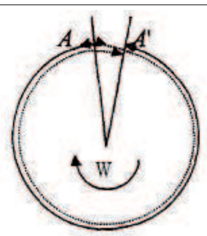
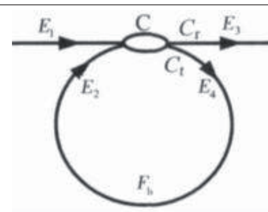
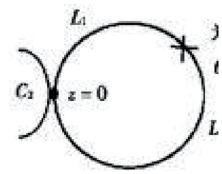
	The first generation	**The second generation**	**The third generation**
Name	Interferometric FOG	Resonant FOG	Stimulated Brillouin scattering FOG
Index	Zero-biased stability: (°/h): 8.5129 angle random walk coefficient (ARW) is 0.0841°/h~(1/2)	Zero-biased stability: (°/h): 18.181 angle random walk coefficient (ARW) is 0.05781°/h~(1/2)	The response of threshold power of pump light to temperature is 32.6×10^{-6}°C^{-1}, and the response of beat frequency to temperature is $88.232.6 \times 10^{-6}$°C^{-1}
Main features	The SAGNAC effect is enhanced by using multi-turn fiber coils. A double-beam ring interferometer consisting of multi-turn single-mode fiber coils can provide high accuracy and will inevitably make the overall structure more complex	Ring resonator is used to enhance SAGNAC effect and cycle propagation is used to improve accuracy. Therefore, shorter optical fibers can be used	Conversion of light power into light wave by stimulated Brillouin scattering
Specific classification	DepolarizedI-FOG ALLPM-fiberI-FOG IOCI-FOG	ALLfiberR-FOG IOCR-FOG(MOG)	SBS-FOG(B-FOG)
Sample grap			
Stage of development	Practical stage	Stage of transition from laboratory to practice	Theoretical stage
Application area	Aircraft and vehicle navigation, missile guidance, precision space vehicle, submarine [11]	—	—
Advantages	Low random walk, long life, high reliability, no mechanical vibration, anti-electromagnetic interference, light weight, small size, high sensitivity, wide bandwidth, easy to realize multi-channel or distributed sensors [12]	Compared with I-FOG, the theoretical accuracy is more accurate and the volume is smaller	Simple structure, few parts, firm and stable, strong shock resistance and acceleration resistance, long service life, high sensitivity and resolution, instantaneous start-up in principle and wide dynamic range [13]
Shortcomings	Optical fibers are greatly affected by temperature. As the length increases, the cost becomes more and more expensive, the accuracy cannot be improved, and the miniaturization cannot be achieved [14]	The production cannot meet the current demand	Generation and stable output of single-frequency SBS laser, locking phenomenon, polarization fluctuation, temperature effect

Table 2.
The classification of FOG.

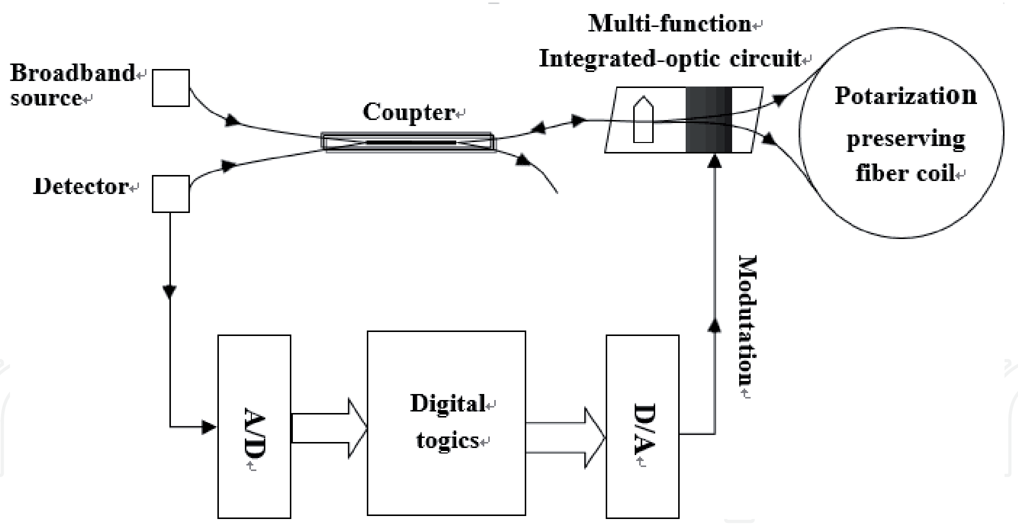


Figure 2.
The basic composition of FOG.

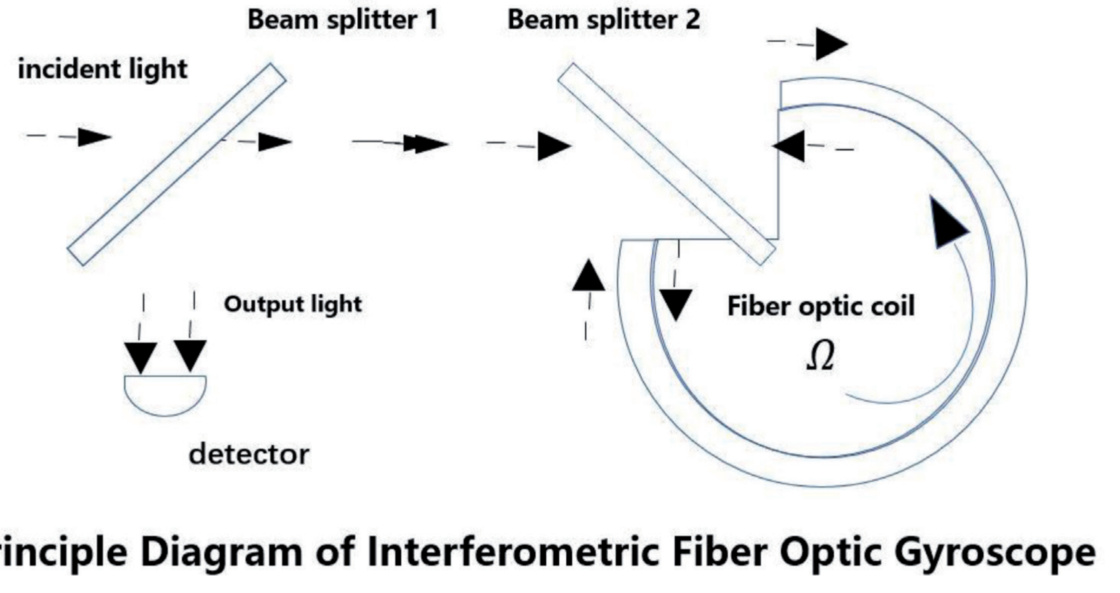


Figure 3.
The principle of interferometric FOG.

clockwise, respectively. The two beams will interfere at the beam splitter. If the closed optical path does not rotate relative to the inertial space, the two beams pass through the same path and the phase difference is zero. If the closed optical path has a rotational angular velocity relative to the inertial space, the two beams experience different paths with a slight optical path difference. At the same time, the two beams also have a phase difference, which is the Sagnac effect. IFOG uses Sagnac effect to measure rotation angular velocity. The interferometric FOG is actually the Sagnac interferometer [16]. Its schematic diagram is shown in **Figure 3**.

2.4.2 Resonant FOG

The basic principle of resonant FOG is Sagnac effect. The core device of resonant FOG is fiber ring resonator. The limit sensitivity of resonant FOG is determined by the shot noise of photodetector, so it is closely related to the resonant characteristics of resonant cavity.

Resonant Fiber Optic Gyroscope (RFOG) is also based on the clockwise and counterclockwise optical path changes caused by Sagnac effect. The light wave propagates in the optical fiber loop with periodic interference. The light source with narrow linewidth has the characteristics of long coherence, which results in resonance effect. The change of optical path of light wave propagating in optical fiber loop will lead to the change of resonance frequency point. The corresponding angular velocity can be obtained by obtaining the change of the resonance frequency point of the light wave in a certain direction.

RFOG is divided into two types, including reflective and transmission ring resonators. As shown in **Figure 4**, the reflective type uses the reflection spectrum of the resonator to detect dark peaks, while the transmission type uses the transmission spectrum of the resonator to detect bright peaks [17].

The basic principle of RFOG is Sagnac effect. For resonant gyroscope, its output detects the frequency difference of clockwise and counterclockwise beams propagating in the resonant cavity. Because it is sensitive to Sagnac frequency shift by using the steep resonant curve of the resonant cavity, it greatly reduces the length of the sensitive fiber optic coil. When the resonant cavity is stationary, the frequency difference between the two beams is zero. When the resonator rotates, the frequency of two beams of light propagating in opposite directions changes, and the frequency difference of the two beams is linear with the rotational speed. It is this frequency difference signal that the resonator gyroscope detects. Its expression is [18, 19]

$$\Delta_{v} = v_{ccw} - v_{cw} = \frac{4A}{\lambda L}\Omega = \frac{D}{\lambda}\Omega \tag{1}$$

where A is the area of the resonator, D is the diameter of the resonator, and $4A/\lambda L$ or D/λ is the scale factor of the gyroscope. Therefore, as long as $\Delta\nu$ is measured, the rotation rate Ψ can be learned.

2.4.3 Stimulated Brillouin scattering FOG

Stimulated Brillouin scattering occurs when the intensity of the transmitted light in the fiber ring reaches threshold level. The frequency of the scattered light varies with the rotation angular velocity of the fiber ring due to the influence of Sagnac effect. The rotation angular velocity of the optical fiber ring can be obtained by detecting the frequency of the scattered light produced by CW and CCW light and beating the frequency.

Stimulated Brillouin FOG is a gyroscope consisting of Brillouin laser. It is an optical product of Ring Laser Gyroscope (RLG). Its basic principle is shown in **Figure 5**. When the incident light intensity exceeds the Brillouin threshold of the optical fiber, due to the electrostrictive effect, a moving acoustic wave will be generated

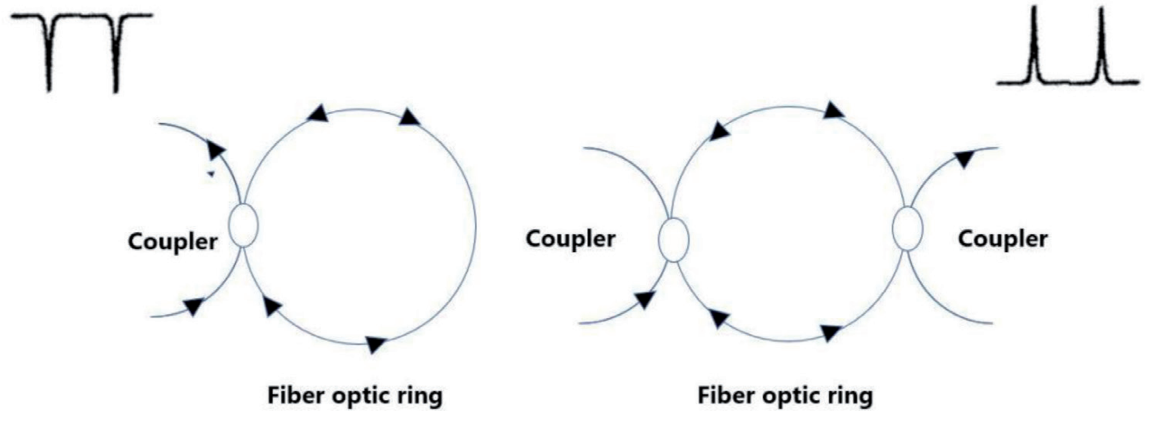


Figure 4.
The reflective resonator.

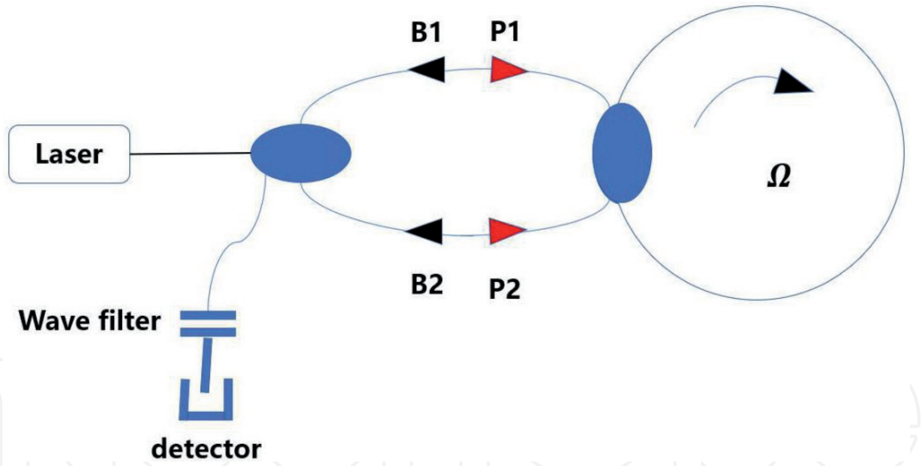


Figure 5.
The principle diagram of stimulated Brillouin FOG.

in the optical fiber. The existence of this moving acoustic wave leads to the generation of stimulated Brillouin scattering (SBS). When two pumped beams (P1 and P2) are incident into the ring resonator in the opposite direction at the same time, two Brillouin beams (B1 and B2) opposite to the pumped beams will be generated. If the ring resonator is stationary, the two Brillouin beams are proportional to the frequency difference, Dn. Two Brillouin beams are photosynthesized and beat frequency is generated. The rotation rate of the optical fiber resonator can be obtained by measuring the beat frequency, Dn.

The rotation angular velocity of the optical fiber coil is linearly related to the frequency difference of the output two Brillouin beams. The ratio factor is $\frac{4S}{\lambda \cdot nL}$, where λ is the wavelength of the pumped light, L is the length of the optical fiber coil, n is the refractive index of the optical fiber coil, and the area S is the area surrounded by the optical fiber coil.

2.5 Characteristics of FOG

1. All solid-state integration, the instrument is firm and stable, and has strong shock resistance and acceleration resistance.

2. The optical path is increased by the optical fiber ring, and the detection sensitivity and resolution are increased by several orders of magnitude compared with the laser gyroscope. Thus, the locking problem of the gyroscope is effectively overcome.

3. Without mechanical moving parts, there is no wear and tear problem, so it has a long service life.

4. The propagation time of coherent beams is very short and can start instantaneously in theory.

5. It is easy to adopt integrated optical technology. The signal is stable and reliable. It can be output digitally and connected directly with the computer interface.

6. It has a wide dynamic range.

7. It has simple structure, low price, small volume, and light weight [15].

2.6 Key technological breakthroughs of FOG

Although FOG has many advantages over other gyroscopes, it still has some shortcomings because of the imperfect technology. Thus, we can employ some solution showed in **Table 3** to obtain better performance for FOG.

2.7 State of the art of FOG

FOG has different development and research status in different countries and has its own characteristics. The United States, Japan, France, Germany, Britain, and China are the main developing countries of FOG. Europe and the United States have obvious advantages in the research and development of high-precision FOG, while Japan pays more attention to the commercial application of low-precision FOG [13]. China and other countries also attach great importance to the research and promotion of FOG.

The United States is a pioneer in developing and applying FOG. Its contractors, universities, and government agencies are developing key technologies, such as Litton, Honeywell, KVH, Norhrop Grumman, and Draper Laboratory. These companies are mainly engaged in the research and development of high-precision FOG [23], providing services for the U.S. military and aerospace departments. They have also done very well in the development and production of FOG. At present, many types of FOG have been put into use in the United States.

Japan is also a big country in the research and production of FOG. The research institutes include the cutting-edge technology laboratory of Tokyo University, Hitachi Corporation, Mitsubishi Corporation [13], Japan Aerospace Electronics Company (JAE), Mitsubishi Precision Instrument, and so on. These companies

Technical direction	Causes	Influence factor	Solution
Angular random walk coefficient (noise measurement conditions)	Back Rayleigh scattering in optical fibers and back scattering from optical interfaces	Relative intensity noise of light source, thermal phase noise of optical fiber coil and photodetector noise	Noise filtering technology; noise elimination technology [20].
Scaling temperature compensation	Important devices are sensitive to temperature	Average wavelength of light source	Broadband Erbium doped fiber light source (SFS) [21] with better wavelength stability or wavelength control measures
		Feedback channel gain	The second closed-loop feedback control loop is added based on the closed-loop feedback control circuit of FOG by using error signal [22]
Environmental adaptability	Vibration, shock, acceleration, etc.	Poor environmental adaptability	Expanding the dynamic range of measuring rotation velocity
Improving sensitivity and accuracy of detection	Poor performance of functional components	Low sensitivity and accuracy	Improving matching and phase shift of functional components [12]

Table 3.
The key technological breakthroughs of FOG.

Country	Company	Main performance: Zero bias stability	Application	Reference
America	Litton Industries Inc.	0.008°/h	The SCIT experimental inertial device was developed in 1988. Then the CIGIF demonstration system flight test device, inertial measurement system and GPS/INS integrated navigation system are developed	[25]
America	Honeywell International Inc.	0.00023°/h	It studies high-performance interferometric FOG, whose products are widely used in satellite, rocket, aircraft and other aerospace fields	[26–28]
America	Northrop Grumman	<0.005°/h	Its optical fiber technology has matured in the field of low and medium precision, and has been commercialized. Its main customers are some major airlines in the United States. Its products can be used in land, sea and air fields	[26]
Japan	Hitachi, Ltd.	Low and medium precision civil products of 10°/h	Its optical fiber technology has matured in the field of low and medium precision, and has been commercialized. Its main customers are some major airlines in the United States. Its products can be used in land, sea and air fields	[29]
Russia	Fizoptika	0.05°/h	Its FOG has been commercialized. The product models are VG949, VG941B, etc.	[30]
France	EuroFOG	Serialization from 10°/h to 0.01°/h	Tri-axis scheme is adopted below 0.1°/h, and single-axis scheme is adopted at 0.01°/h	[26, 30]
France	IXSea	0.003°/h	With a number of key patents of FOG, its application fields include offshore, underwater and space applications	[26]
Germany	LITEF	<0.01°/h	Product applications cover space, air, land and water, as well as military and civilian applications. After 2003, integrated navigation system will be provided to provide position, course and attitude information for military reconnaissance vehicles	[26]
China	Beihang University	0.005°/h	It has a complete production line of FOG	[30]
China	China Aerospace Times Electronics Co. Ltd.	0.01°/h	Its product mainly used in the field of aeronautics and astronautics	[30]

Table 4.
The application of FOG in the world.

attach great importance to the practicality of FOG. They have mass-produced a variety of levels of FOG, especially those of medium and low precision. They are in the forefront of the world in practicality and can be applied to environmental protection, vehicle navigation, industrial control, and so on.

The research and development of FOG in Western European countries mainly focus on France, Italy, and Russia. These countries attach great importance to the development of military applications of FOG. These countries are mainly committed to the development of low performance FOG equipment with drift rate greater than 1 (°)/h, Navy and air force. The first generation of FOG has been put into production. For example, PHINS series FOG, which is produced by IxSea Company in France, has been applied to inertial navigation and deep-water operation. Civitanavi Systems, Italy, based on proprietary FOG technology, developed a FOG [24] for attitude stabilization and navigation of satellite launchers.

FOG has different research and application in different countries. From **Table 4**, we can see the application of FOG in different companies in the world.

3. Conclusion and expectation

After more than 30 years on research and exploration, the technology of FOG has achieved a high level. While guaranteeing the accuracy and meeting the current requirements, FOG is gradually developing in the direction of low cost, miniaturization, high reliability, and long life.

FOG has been mainly used in astronautics, including spacecraft, satellite, aircraft, etc., and it is also widely used in civil fields such as ship, automobile navigation, mine, and so on. Based on different zero bias stability, their applications are different. If the bias stability is greater than 10°/h, it can be employed in land vehicle navigation, robot attitude control, and camera or antenna stabilization device. And when the bias stability is small ranging from 0.001 to 0.01°/h, FOG can be used in aerospace inertial navigation system and navigation. Whereas, in precision spacecraft applications, the zero bias stability required for precise aiming and tracking is less than 0.001°/h [30].

FOG is a type of angular rate measurement instrument based on Sagnac effect. It has advantages of no moving parts and wearing parts, small size, light weight, large dynamic range, fast start-up, long life, low cost, impact-resistant structure, flexible design and simple production process, etc. [29, 31]. It is broadly used in inertial navigation systems such as aviation, navigation, and aerospace, and is not in the direction of high precision. Continuous development [29, 32] with the development of modern microelectronics technology, optoelectronics technology, and signal processing technology, FOG will continue to mature; its application will continue to expand. In the future, there will be a greater stage in the field of inertial measurement.

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