Special Optical Fiber Technology and Industry Development Trends

1. Introduction

In the paper Dielectric-fibre Surface Wave-guides for Optical Frequencies[1] published by Gao Kun in 1966, it was first proposed to prepare circular cross-section glass dielectric fiber waveguides with very low transmission loss by controlling the purity and composition of the glass to achieve effective transmission of light wave signals, single-mode fiber-guided light (the principle is shown in Figure 1). A few years later, the first low-attenuation fiber was successfully developed by Corning, and in 1977, the first communication optical cable was laid underground in Chicago, realizing the application of fiber optic technology "from 0 to 1". Subsequently, in communications technology, the fiber optic completed the "fiber replacing copper" project. Meanwhile, two "new tracks" of sensing and lasers have also developed at high speed, which, although not known as the "protagonists" in new applications of fiber optics, have played an indispensable role as components in high-power lasers, aerospace, energy, marine sensing and monitoring, and biomedical applications.

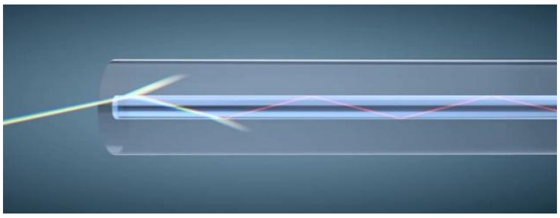


Figure 1 Light-guiding Principle of Single-mode Fiber

There are two application lines for photoelectric sensing technology: first, it is hoped to maximize the use of the existing fiber optic cable base, with the infrastructure or the standard quartz single-mode fiber optic communication system deployed nearby, (loss has been reduced to near 0.1 dB /km @ 1550 nm wavelength), to demodulate the information during transmission for testing the health of the infrastructure (higher requirements for demodulation, with some potential security concerns); second, to enhance the performance of certain indicators by optimizing the communication single-mode fiber. For example, compared to quartz standard single-mode optical fibers, the structure and material composition of polarization-maintaining, multicore, microstructured, doped rare-earth elements, multicomponent glass, and plastic optical fibers are more complex[2], which is why they are called "special optical fibers". However, regardless of the technological route, optical fibers are gradually forming a "nerve" network on the surface of the earth, "sensing" for defense and industry.

Let's use a "fiber optic tree" to see the industry (Figure 2), which has been developed for more than half a century, with its upstream areas (root part) mainly involving glass, polymer materials, manufacturing technology, etc., where a large number of research institutes and enterprises around the world still contribute their wisdom in this basic condition; downstream applications (branch part) involving optical communication, fiber optic laser, optical sensing, biomedical and other major fields, where the advantages of single-mode optical fiber applications are notable (high bandwidth, flexible, anti-jamming, chemically stable, cost-effective), occupying a dominant position. However, special optical fiber has played a significant role in the development of a new generation of science and technology, not only upgrading the technical content of fiber optic technology, supporting and promoting the development of new infrastructure for the "5G" information and communications industry, but also playing vital roles in the general environment (rainbow and dark clouds) - the construction of the "Belt and Road" international fiber optic cable trunk strategy and breaking through the technical barriers in the trade war.

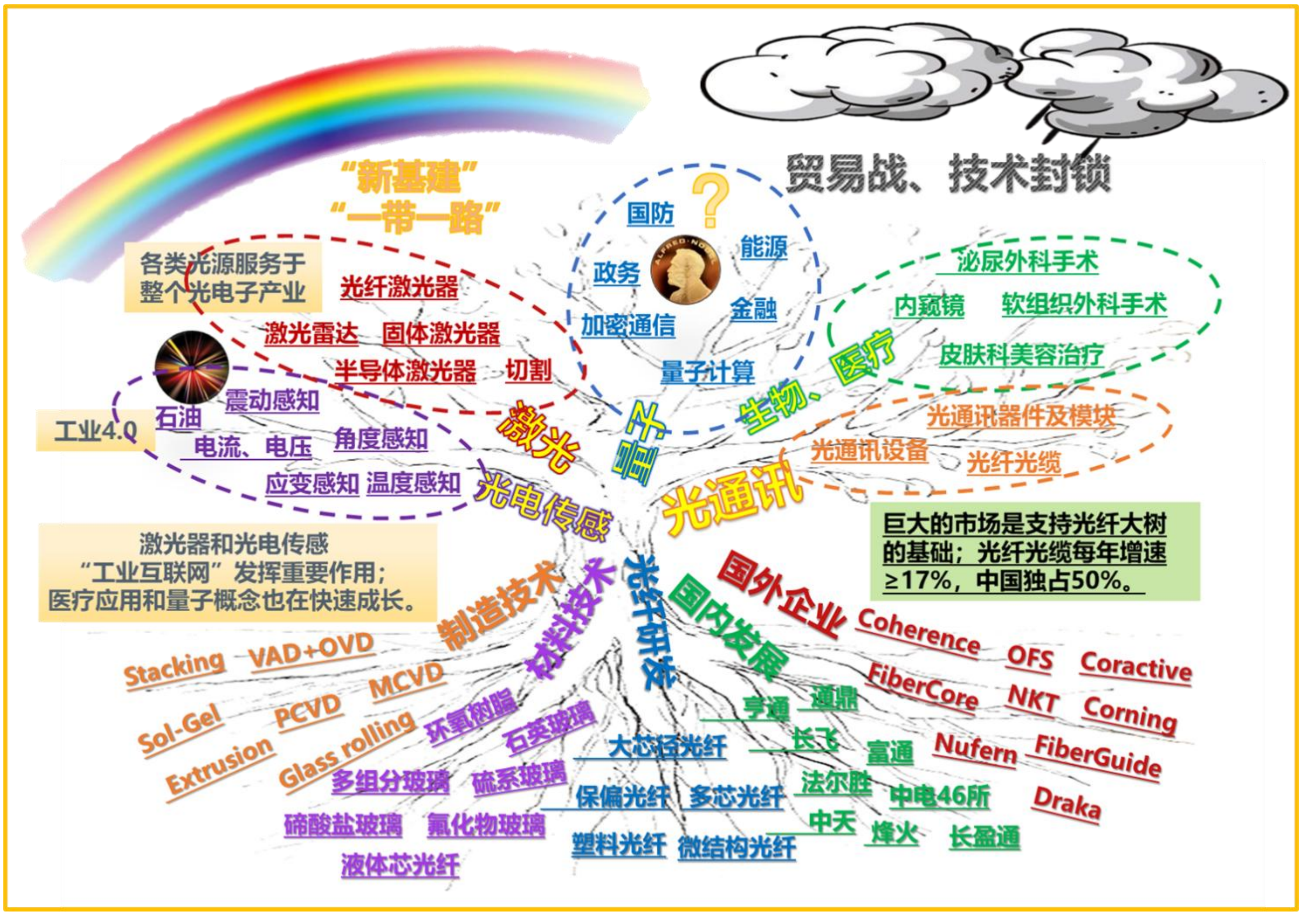


Figure 2 Fiber Optic Development Tree

2. Classification of special optical fiber

With the rise and development of the Internet of Things, big data, and cloud computing, man has a higher standard of communication; in parallel, a large number of novel applications in the field of photoelectric sensing and lasers require the use of different structures, or chemical elements, to prepare and synthesize more reliable and diverse optical fibers.

The purpose of any technological development is to solve a practical problem, and special optical fibers often start from customized research, so the types of special optical fibers are very diverse. After half a century of accumulation, some rules can be sorted out from them (fibers for non-optical applications are not considered here).

As shown in Figure 3, special optical fibers can be divided into microstructured fibers (typical representative: hollow-core bandgap-type photonic crystal fiber), multi-core fibers, polarization-maintaining fibers (typical representative: panda-type polarization-maintaining fibers), and shaped-core fibers (typical representative: square-structured fiber-core fibers) and so on, according to their structures.

There are also different classifications of optical materials, of which quartz glass material, a very stable glass substrate, has undergone decades of testing and development and can be synthesized to strictly control glass purity; rare earth doped quartz glass is also a type of highly important optical material, such as erbium doped fiber amplifier (EDFA)[4], which has a remarkable application effect in the field of fiber optic communication due to its operating wavelength coinciding with the lowest attenuation wavelength of quartz glass (1550 nm).

However, in the early days before the choice of quartz glass materials, there were also fluoride glass, sulfur glass and other optical glass materials suitable for drawing optical fiber, known as "multi-component glass" (also known as "soft glass").

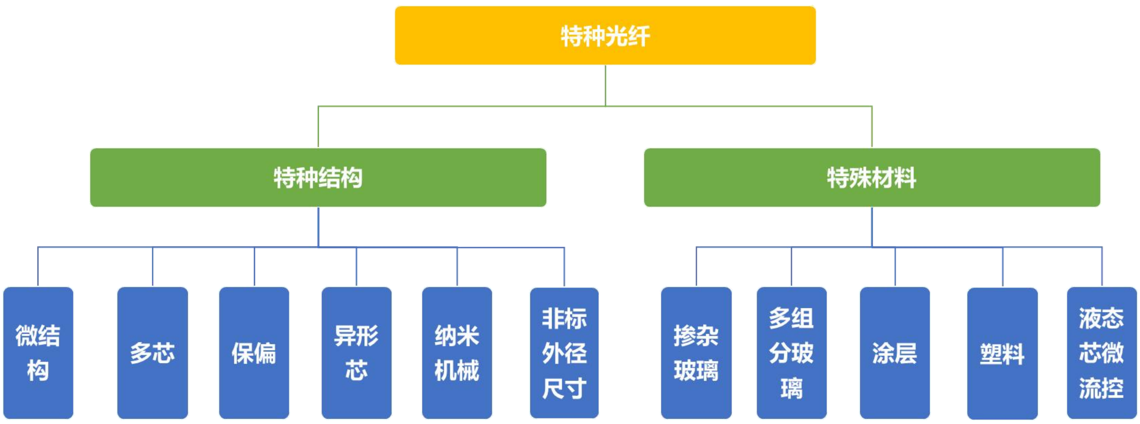


Figure 3　Special Fiber Classification

2.1 Development history of special optical fibers in structural classes[3]

Optical fibers are inevitably subjected to external stresses during use, causing them to exhibit a certain degree of polarization mode dispersion. 1972 saw the first study of birefringence in single-mode fibers by F.P. KAPRON, which showed that the birefringence properties and information transmission of single-mode fibers are related to the fiber length. Since then, polarization-maintaining fibers (e.g., panda-type polarization-maintaining fibers), which can maintain the polarization state of light waves and reduce polarization dispersion, were widely studied and applied in the 1980s. Figure 4 shows the structural development of special optical fibers.

The first photonics crystal fiber was born in 1996 in the form of a solid core surrounded by a cylindrical hole in a hexagonal array. Subsequently, hollow-core photonic crystal fibers were developed in various configurations, such as the hollow-core bandgap photonic crystal fiber by R. F. Cregan from the Optoelectronics Group at the University of Bath in 1999, and the hollow-core anti-resonant fiber by the Vapor Phase Photonic Materials Group at the University of Bath in 2010. The attenuation level of optical fiber also continues to be optimized, trending to surpass that of single-mode fiber for communication.

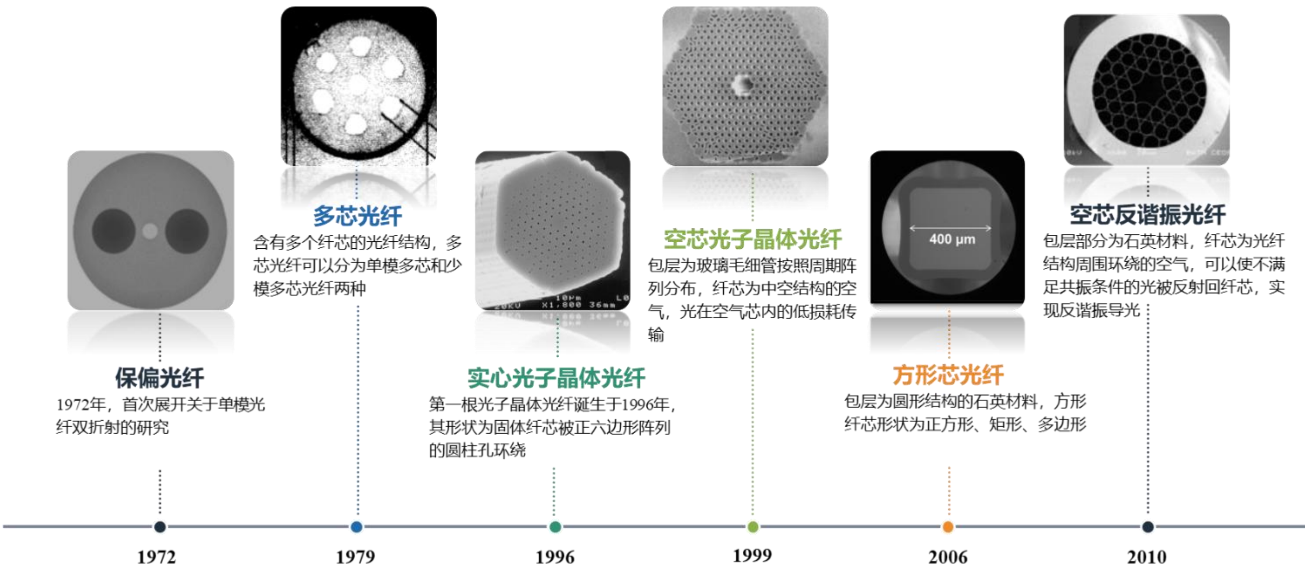


Figure 4 Development History of Special Optical Fiber Structure

In 1979, S.INAO proposed the concept of multi-core optical fiber in order to develop a high-integrity, large-core fiber optic cable structure. After theoretical refinement and experimental research, France Telecom produced a field-usable plum-shaped four-core single-mode fiber in 1994, making the multi-core fiber practical and commercialized. Multi-core fiber offers the possibility to increase the capacity of fiber optic communication, and due to its own sensitivity, its application in the field of fiber optic sensing has become diversified. At present, light sources or optical receiving devices can still only be connected by single-mode fibers, so to promote multicore fiber, the primary problem is the connection with single-mode fibers, and the main solutions are fiber bundles, spatial lenses and polymerization waveguides.

2.2 Development history of material-based special fiber[3]

In 1952, the formation and structure of phosphate glasses were investigated at the University of Southampton, UK. Phosphate glasses can form both basic structural constituent units and lone pair electrons, so that high concentrations of rare earth doping can be achieved to obtain laser output. This type of optical fiber is mainly used for short-distance signal transmission and image transmission, and due to different proportions of material composition, the optical properties of the glass produced also vary, making a wide variety of multi-component glass, and relatively low manufacturing costs, with the current main types including heavy metal oxide glass, fluoride glass, sulfide glass, tellurite glass, and "Schott "system glass, etc. Figure 5 shows the development history of special optical fiber materials.

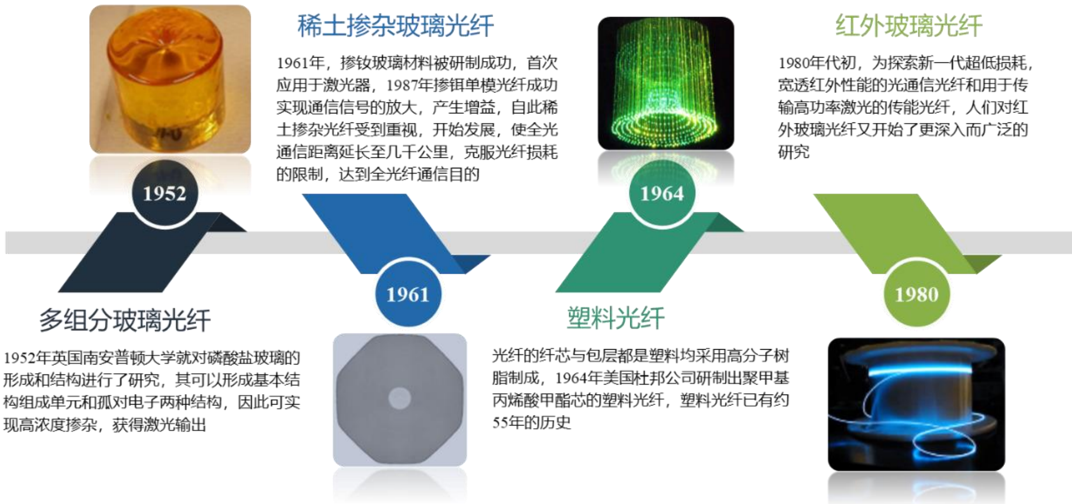


Figure 5　Development History of Special Optical Fiber Materials

In 1961, neodymium-doped glass was successfully developed and first applied to lasers; in 1987, erbium-doped single-mode optical fiber successfully achieved the amplification of communication signals to produce gain[4], which extended the all-optical communication distance to several thousand kilometers and overcame the limitation of fiber loss to achieve all-fiber communication purpose. Since then, rare-earth doped optical fibers have been valued, but doping is the main limiting factor for the radiation resistance of optical fibers, which has also become a key direction of scientific research.

The plastic fiber with polymethyl methacrylate core developed by DuPont in 1964 has now become an ideal transmission medium for short-distance communication networks, with a significant position in lighting decoration, future home intelligence, office automation, industrial control networking, vehicle-mounted airborne communication networks and short-distance data transmission in multimedia devices (picture from a foreign plastics journal, article name *Key Points of Plastic Optical Fiber Product Development Technology*).

In the early 1980s, a new generation of infrared glass optical fibers for information transfer and light energy transmission was widely and intensively explored (picture from Fiber labs products in Japan), especially for laser transmission in the mid-infrared band. Mid-infrared laser technology is growing mature, but still has problems such as damage to the working material caused by the accumulation of thermal effects, destruction of beam quality by thermal lensing effects, and limited laser power increase.

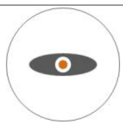
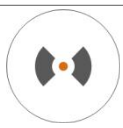
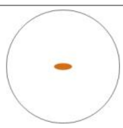
3. Polarization-maintaining fiber

As one of the most mature and widely used special optical fibers, polarization-maintaining fiber has undergone several "five-year plans" in the domestic optical fiber sensing industry and has formed complete sets of preparation and application technologies.

3.1 Classification and application of polarization-maintaining fiber

Before 1980, it was very difficult to achieve polarization state control in optical fibers to reduce mode dispersion brought by polarization. After decades of development, driven by the maturity of polarization-maintaining fiber technology in the United States, Japan and Europe, the global polarization-maintaining fiber technology has developed rapidly, including China's polarization-maintaining fiber products being optimized and innovated continuously. Polarization-maintaining fiber is mainly classified by structure (e.g., Table 1) as panda, bow-tie (also known as "butterfly"), elliptical cladding, elliptical core, flat cladding, side groove/side tunnel, and twisted polarization-maintaining fiber, etc.; according to the birefringence coefficient, it can be divided into high birefringence fiber (B~10-4) and low birefringence fiber (B~10-9), and there are various types of technical solutions for both high and low birefringence.

Table 1 Advantages and Disadvantages of Various Types of Polarization-maintaining Fiber

Type	Structure Diagram	Advantages	Disadvantages
Panda polarization-maintaining fiber		Large size of prefabricated rods, stable and suitable for engineering mass production	High stress expansion coefficient, sensitive to temperature changes
Elliptical cladding		Insensitive to temperature	Small prefabricated bars, uneven stress distribution, easy to produce cracks when cutting
Bow-tie		High birefringence coefficient	Small prefabricated rods, difficult to control the geometric size of the fiber core
Elliptical core		Insensitive to temperature, with easy grinding of end faces	Low birefringence coefficient

Polarization-maintaining fibers are used in telecommunications, medicine and sensors, and coherent optical communications and fiber optic gyroscope sensing systems place great importance on the control of polarization states, such as optical coherent reflection (OCR) in medicine, where surgeons are able to distinguish between the vessel wall and their own blockage to achieve "chronic total obstruction of the coronary artery ("CTO") region.

Currently, the panda type polarization-maintaining fiber dominates the commercial polarization-maintaining fiber products, mostly used in fiber optic gyro (FOG). The performance parameters of optical fiber, which directly determine the performance of fiber optic gyro, is the sensitive part and the crucial core component in fiber optic gyro.

In view of the increasing competition between fiber optic gyro and laser gyro and MEMS gyro, and the emergence of a series of new gyroscopes, it becomes inevitable to improve its accuracy and reduce its cost. Thanks to the wide application of fiber optic gyro in aerospace and marine environments, the optical properties such as attenuation, polarization, nonlinearity and geometric size control of the polarization-maintaining fiber have been rapidly optimized and improved, becoming an irreplaceable core part of fiber optic gyro applications. Therefore, in order to realize the lightweight and low cost of high performance fiber optic gyro devices, the cladding diameter of the polarization-maintaining fiber has gradually evolved from 125 μm to 80 μm, 60 μm, and 40 μm or even finer, as shown in Figure 6. With the continuous reduction of the outside diameter of the polarization-maintaining fiber, how to maintain the good performance of the fiber while reducing the outside diameter of the fiber has become a major problem in the design and manufacturing process of optical fiber, and the localization substitution of its melting shaft equipment also needs to be further studied and solved.

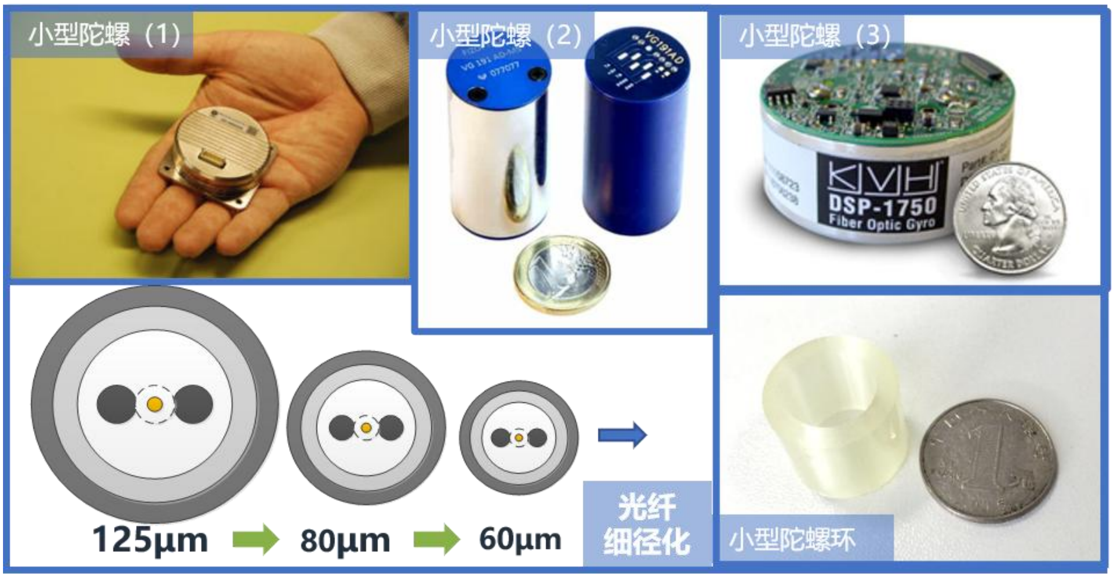


Figure 6 Fiber Optic Gyro Miniaturization, Development Trend of Polarization-maintaining Fiber

3.2 Preparation of panda polarization-maintaining fibers

After decades of development, the development process procedure of optical fiber prepared from quartz glass material is basically finalized and divided into two steps: (1) preparation of prefabricated rods (2) fiber prefabricated rod drawing.

(1) The conventional single-mode fiber preform preparation process mainly uses modified chemical vapor deposition (MCVD), outer vapor deposition (OVD), vapor phase axial deposition (VAD) and plasma chemical vapor deposition (PCVD). The preparation of the polarization-maintaining fiber preform is similar to the single-mode fiber process, in which the core is prepared by MCVD; the deposited single-mode fiber preform is perforated, i.e., two symmetrical parallel holes of the same size are drilled on both sides of the core for laying stress zones; the stress bar is a boron-doped quartz glass containing boron elements. The stress rods (borosilicate glass) are snapped into the two holes to form a complete panda-type polarization-maintaining fiber prefabricated rod, as shown in Figure 7.

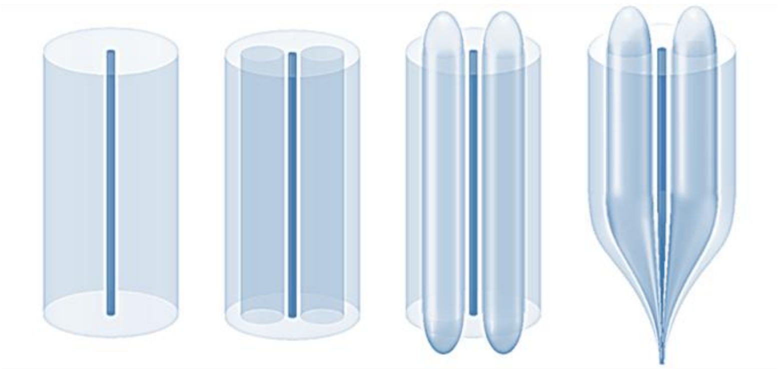


Figure 7 Preparation Process of Panda Polarization-maintaining Fiber

(2) The fiber "drawing" is the "equal scale reduction" process of stretching the prefabricated rod into filaments. Since boron-doped glass and quartz glass have different glass state temperatures, the stresses can be solidified in the glass filaments during the simultaneous drawing process, i.e., stress birefringence is introduced in the fiber core. Due to the difference in coefficients of thermal expansion of the materials, polarization-maintaining fibers are more "delicate" than ordinary fibers, making them more demanding to cut, fuse, bend, and other applied operations.

4. Development status of special optical fiber at home and abroad

As a more mature typical optical fiber for sensing, the development of polarization-maintaining fiber can also reflect the general situation of other special optical fibers, which have experienced the localization from import to the whole industry chain. Especially in the field of fiber optic gyro, many industry experts say that the domestic fiber optic gyro technology has gradually reached the state of "leading" the world from "parallel".

In the 60 years of special optical fiber development, each fiber has its own development cycle, and all have gone through the process from import to localization. Today, there are more than 50 main special fiber companies in the world (Figure 8), mainly in Europe, America and Asia, including NKT Photonics in Denmark, J-fiber in Germany, GLO Photonics in France, Fiber Core in the UK, etc. in Europe; Corning, OFS, Nufern in the US, Coractive, IVG Fiber in Canada, etc. in the Americas; Asia's main companies are mainly concentrated in China's YOFC, FiberHome and YOEC and Japan's Sumitomo, Hitachi, etc.

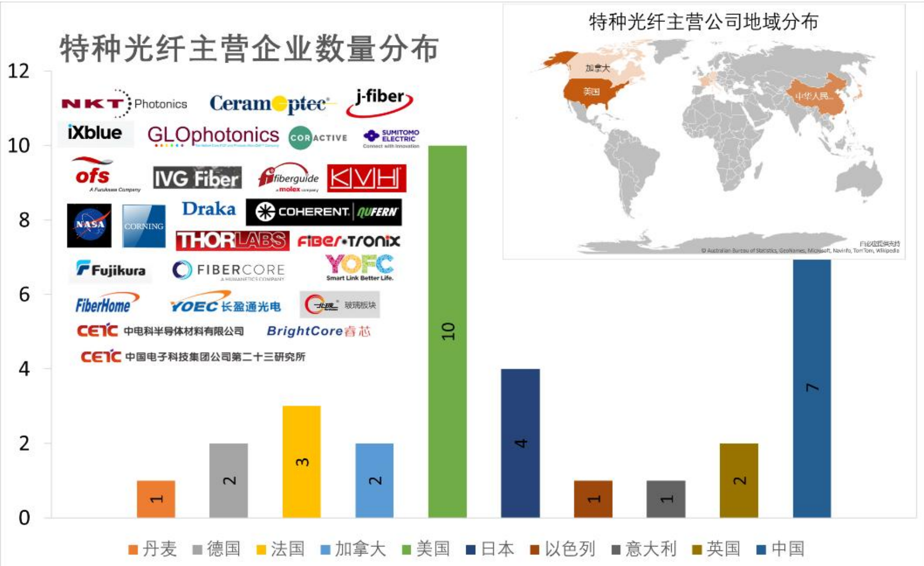


Figure 8 Special Fiber Main Business Distribution

Through the comparison of the same type of products at home and abroad, we found that there is much to study and draw on foreign technology, whose mature products are more flexible and stable in terms of loss, size structure, optical index control, and generally 10 years ahead of domestic technical maturity. More crucially, foreign supporting test instruments developed for special optical fibers are more accurate and comprehensive compared to domestic ones. The possession of good judging means is the basis for promoting the development of technology. If China wants to surpass foreign ones in the field of special fiber, then improving the existing comprehensive capability of special fiber development and supporting technology will be the top priority of special fiber development in the next few years.

On the other hand, the development of special fiber in China has completed the history of "from nothing to something", and now it has entered a new stage of "from something to excellence". The arrival of the "5G" era, and the "Belt and Road" strategy, as well as China's good internal circulation opportunities, have solved the problem of restrictions from the development to the application of special fiber from the root, coupled with the fact that China is constantly injecting new technologies into the industry, so China's special fiber also has the ability of global leading level in some product fields.

5. Conclusion

Understanding the evolution of how special fiber technology got to where it is today will give us a clearer picture of what the future holds. Special fiber is diverse and versatile. With the emergence of new technologies such as the Internet of Things and cloud computing, the demand for special fiber and various new optoelectronic devices is rapidly increasing, thus special fiber, as an emerging industry, is facing huge development opportunities and challenges.

Special fiber will be more deeply used in industrial intelligent equipment, life health monitoring, aviation and marine detection, as well as the energy industry, to become the city's "neural network". However, this still requires the continuous efforts of all industries to promote "standardization", so that special fiber is no longer "special"; we need to work together to solve the problem that special fiber application supporting technology is still dependent on imports, so that special fiber really becomes a "user-friendly" fiber.

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