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Review

Applications and Development of Multi-Core Optical Fibers

Weiping Chen [1], Lei Yuan [1], Bo Zhang [1], Qianqin Yu [1], Zhenggang Lian [1,2,3,*], Yabin Pi [1], Chongxin Shan [2] and Perry Ping Shum [3]

1 Yangtze Optical Electronic Company, Wuhan 430205, China
2 School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450052, China
3 Department of Electrical and Electronic Engineering, College of Engineering, Southern University of Science and Technology, Shenzhen 518055, China
* Correspondence: lianzhenggang@yoec.com.cn

Abstract: The rapid development of information and communication technology has driven the demand for higher data transmission rates. Multi-core optical fiber, with its ability to transmit multiple signals simultaneously, has emerged as a promising solution to meet this demand. Additionally, due to its characteristics such as multi-channel transmission, high integration, spatial flexibility, and versatility, multi-core optical fibers hold vast potential in sensing applications. However, the manufacturing technology of multi-core fiber is still in its early stages, facing challenges such as the design and fabrication of high-quality cores, efficient coupling between cores, and the reduction of crosstalk. In this paper, an overview of the current status and future prospects of multi-core fiber manufacturing technology has been presented, and their limitations will be discussed. Some potential solutions to overcome these challenges will be proposed. Their potential applications in optical fiber sensing will also be summarized.

Keywords: multi-core optical fiber; manufacturing technology; optical fiber sensing; future prospects

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1. Introduction

With the rise and development of the Internet of Things, big data, cloud computing, and artificial intelligence, a large number of novel applications in the field of optical communication, optoelectronic sensing, and lasers require the use of new structures or optical materials to fabricate and synthesize more reliable and diverse functional optical fibers. The purpose of any technological development is to solve a practical problem, so specialty fibers often originate from customized research. Therefore, there are many types of specialty fibers, among which multi-core optical fibers belong to a type of micro-structured fiber. The concept of multi-core optical fibers first appeared in 1979, where it was inspired by the development of high-integration large-core-count cable structures by the team led by S. Inao [1]. They began exploring how to achieve multiple optical transmission channels in a single fiber. However, the technological limitations and immature fabrication methods at that time posed challenges to the practical fabrication of multi-core optical fibers. In the following decades, scientists continued to explore and investigate multi-core optical fibers from theoretical, fabrication, and application aspects, and some noteworthy advances have been achieved.

During the exploration and research phase of multi-core optical fibers, fiber optic communication technology has gone through three eras: the successive optoelectronic regeneration systems era (1977–1995), the amplified dispersion management systems era (1995–2008), and the amplified coherent digital systems era (2008–2020) [2–4]. The introduction of wavelength division multiplexing (WDM) technology has continuously increased transmission capacity, further improved system spectral efficiency (SE); however, in 2006, Desurvire E.B. [5] proposed that optical networks would have to carry a large amount of increased Internet traffic, however, due to the optical nonlinear effects and permanent thermodynamic damage in long-distance fiber transmission, 100 Tb/s may be the capacity bottleneck for commercial standard single-mode fiber transmission systems, indicating the ultimate technological limit of the physical layer and the end of the "optical Moore's law". This viewpoint has been continuously verified in advanced research results in the spatiotemporal dimension [6,7]. In practical terms, the transmission bandwidth of backbone network fibers doubles every 9 to 12 months, and the bandwidth per fiber connection shows an exponential growth trend from Gbps to Tbps, Pbps, and Ebps. This means that in the next 10 years, each fiber in the backbone network will require a capacity transmission on the order of Pbit/s, and the core network will require a capacity transmission on the order of Ebit/s to meet the demand for high-speed, large-capacity, long-distance information transmission [8,9]. Under such circumstances, multi-core optical fibers have once again attracted the attention of researchers because they can offer much higher transmission capacity than conventional single-core fibers. Researchers are exploring how to achieve higher core numbers and larger transmission capacities. The introduction of Spatial Division Multiplexing (SDM) technology enables multi-core optical fibers to support more independent transmission channels, providing higher transmission capacity. Multi-core optical fibers offer new insights into increasing optical fiber communication capacity, presenting a fresh opportunity for development in the field of optical communication [10,11].

However, to date, multi-core optical fibers have not been widely and systematically applied in the field of communication. This is mainly due to the relatively complex system involved in the fabrication and maintenance of multi-core optical fibers, leading to increased manufacturing and maintenance costs. In comparison to single-core optical fibers, the engineering application of multi-core optical fibers may require more technical expertise and resources. Additionally, the technology of multi-core optical fibers is relatively new, with related fabrication and debugging techniques still undergoing continuous development and improvement. Typically, before large-scale application, it is necessary to ensure the stability and maturity of the technology. Meanwhile, in current communication systems, single-mode single-core optical fibers are already capable of meeting the majority of requirements. Considering future capacity transmission demands in the communication field, the introduction of new mature multi-mode optical fiber technology is less challenging and more adaptable compared to the introduction of multi-core optical fibers. Consequently, the development pace of multi-core optical fibers technology in the communication field is relatively slow.

In contrast, as multi-core optical fibers, in addition to possessing the inherent characteristics of standard optical fibers, exhibit features such as multi-channel transmission, high integration, spatial diversity, flexibility, and multifunctionality, they have garnered increasing attention in optical sensing systems. Unlike standard single-mode fibers (SMF), multi-core optical fibers allow the implementation of traditional point sensing principles to achieve simultaneous measurement of multiple parameters. Meanwhile, the distributed sensing technique based on backscattered light in multi-core optical fibers, as well as Optical Frequency Domain Reflectometry (OFDR) technology, enables the extraction of tangential strain characteristics generated at the edge cores during the bending of multi-core optical fibers. This can be applied in directional bending and shape sensing applications. Furthermore, enhanced strain measurement accuracy can be achieved by inscribing Fiber Bragg Gratings (FBGs) on the multi-cores. Simultaneously, multi-core optical fibers provide an opportunity for configuring Spatial Division Multiplexing (SDM) systems with multiple distributed sensing technologies. Therefore, the use of multi-core optical fibers facilitates multi-parameter sensing, improves sensing performance, extends sensing distances, and expands sensing dimensions. These characteristics mean that multi-core optical fibers have broader prospects in the field of optical sensing than SMF.

Thus, this review article will primarily delve into the origin of multi-core optical fibers, specifically their applications in the field of communications, followed by a research summary. It will emphasize the application prospects of multi-core optical fibers in optical sensing systems, the field of sensing, and laser applications. The preparation techniques of multi-core optical fibers will also be described in conjunction with their applications.

2. The Application of Multi-Core Fiber in Communications

Drawing from the inaugural chapter of this academic treatise, we can deduce the following assertions: As we entered the 21st century, the velocity of actual demand for internet traffic has surpassed the rate of capacity expansion in optical transmission systems. Consequently, the imperative to enhance the channel rate, system capacity, and transmission distance of optical fibers has grown progressively more urgent. This chapter aims to delve into the progress of multi-core fibers within communication systems, particularly emphasizing the investigation of optical fiber system capacity and transmission distance within the realm of optical communication technology.

The initial research and technological verification of multi-core fiber started when the concept of multi-core fiber was first proposed in 1979. In collaboration with France Telecom and Alcatel, deep research was conducted on the manufacturing technology of multi-core single-mode fiber preforms and drawing techniques. In 1994, the FCVD process (chemical vapor deposition using a graphite high-frequency induction furnace) was used to manufacture cladding tubes and core rods. Through grinding and splicing, as well as nesting and stacking methods, a four-core single-mode fiber with a length of over 100 km in the shape of a plum blossom was successfully produced [12].

In 2008, the EXAT organization established in Japan brought together researchers from industry, academia, and national research institutes, and proposed a new generation of fiber optic technology, including multi-core fiber, multimode control, and multilevel modulation [9]. The application research of multi-core fiber in the field of communication, with the goal of creating higher data transmission capacity, entered the fast lane, as shown in Figure 1, in which it can be see that the capacity of multi-core fiber has continued to increase from this time.

In 2011, the National Institute of Information and Communications Technology in Japan and the OFS Corporation in the United States became leaders in the forefront of multi-core fiber technology application. They achieved a huge information capacity of 100 Tb per second through the parallel transmission capability of a 7-core fiber [13,14]. This breakthrough not only surpassed the limit of transmission capacity of single-mode fiber, but also brought significant technological progress to the field of communication. Subsequently, in 2012, multi-core fiber technology made new breakthroughs with the emergence of 12-core and 19-core fibers, once again pushing the limits of data transmission capacity to 1.01 Pb/s (1010 Tb/s) [15,16]. This significant increase in transmission capacity enables communication networks to process and transmit large-scale data flows more efficiently. In the same year, a new type of few/multimode fiber was successfully applied in the field of communication through the employment of Frequency Division Multiplexing (FDM) technology [17]. The emergence of this technology brings more diversified possibilities for the development of multi-core fiber technology in the field of communication. Multi-mode multi-core fiber not only possesses the low loss and high bandwidth characteristics of few/multimode fiber, but also has the parallel transmission capability of multi-core fiber [18], achieving a transmission capacity of 1.05 Pb/s (1050 Tb/s).

Since 2012, much research has been devoted to enhancing the materials and structures of multi-core optical fibers. By refining the material properties and structural design of the fibers, transmission efficiency and bandwidth have been improved. Additionally, increasing the number of cores or the number of modes within each core in multi-core optical fibers has been explored to enhance the transmission capacity. In single-mode scenarios, the development of multi-core optical fibers has progressed from 7 cores to 12 cores, 19 cores, 22 cores [19], and 32 cores [20]. By increasing the number of cores, more parallel channels for transmission have been achieved, resulting in improved transmission capacity and data throughput. In few/multimode scenarios, the combination of multi-core structures has led to the emergence of 3-mode 12-core fibers [21,22], 6-mode 19-core fibers [23–26], and 3-mode 38-core fibers [27,28]. By increasing the number of cores and modes, few/multimode multi-core optical fibers are capable of simultaneously transmitting multiple independent signals. It is worth noting that a communication system utilizing a 3-mode 38-core fiber has achieved a transmission capacity of 10 Pb/s [28], further enhancing the data transmission capacity and efficiency. This has expanded the application range of multi-core optical fibers in the field of communication and brought greater flexibility and scalability to scenarios such as short-distance transmission and local area networks.

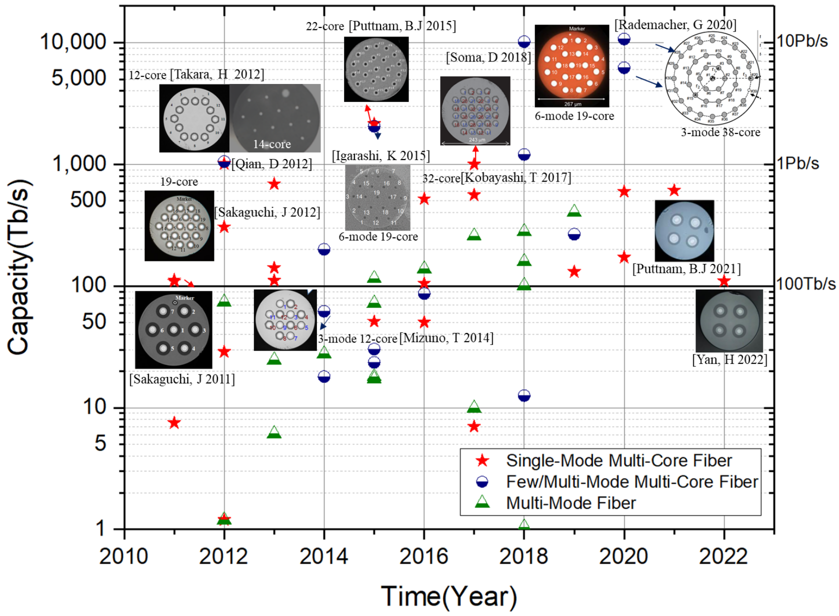


Figure 1. Development trends in capacity for single-mode, few/multimode multi-core, and multi-mode fibers [13–16,18–21,23,26–30].

From 2020 onwards, with the further development of multi-core fiber technology, researchers began to focus on how to achieve more data transmission with limited communication resources and overcome the challenges of increasing fiber diameter and difficulty in fabricating fan-in/fan-out devices [29,30]. In particular, the team led by Puttnam B. J achieved a transmission capacity of 610 Tb/s using a 125 µm cladding diameter four-core fiber, which signifies a breakthrough in maintaining the mechanical performance of the fiber under the limitation of fiber diameter and achieving higher data transmission rates.

Transmission distance is another important metric for multi-core fiber in the field of communication. Although the main focus of multi-core fiber is to improve transmission capacity and bandwidth, extending the transmission distance is also necessary. As shown in Figure 2, compared to multimode fiber [31–35] and few/multimode multi-core fiber [36,37], single-mode multi-core fiber utilizes a single-mode transmission mode, which can effectively reduce crosstalk and interference between different cores, thereby maintaining low loss and high-quality signal transmission. This allows single-mode multi-core fiber to maintain low signal attenuation and distortion in long-distance transmission, making it more advantageous for long-distance transmission [38–42]. Currently, a 12-core fiber is capable of transmitting at a capacity of 105 Tb/s, covering a distance of 14,350 km.

Overall, the application of multi-core fiber in the field of communication has brought many significant improvements and breakthroughs, evolving from single-mode to few/multimode, from fewer cores to more cores, going through three stages: initial research on the multi-core fiber concept (1979–1994), technological fabrication improvements (1994–2008) [43–45], and modernized high-density and high-capacity transmission (2008-present). In the future, multi-core optical fibers are expected to become the typical representatives in spatial division multiplexing (SDM) systems, marking the fourth major era.

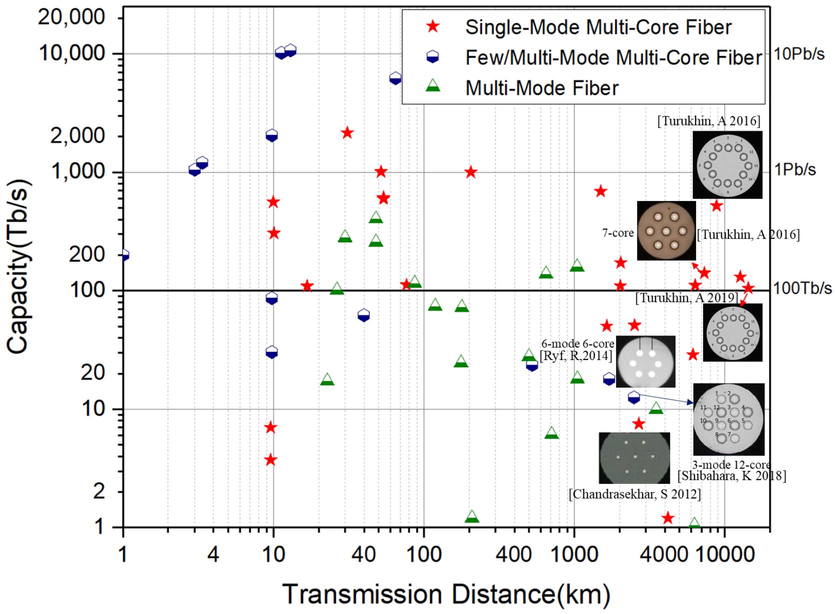


Figure 2. General capacity development relationship of single-mode, multimode multi-core fiber, and few/multimode fiber in terms of transmission distance [36–38,40,41].

However, up to now, the modernization, engineering, and commercial development of multi-core optical fibers in the field of communication have not been realized due to issues such as technical complexity, technological maturity, and uncontrollable costs. The following are the improvement directions for the rapid development of multi-core optical fiber technology:

(1) Reducing transmission loss: although multi-core fiber already possesses low loss characteristics, transmission loss can be further reduced by improving core design, optimizing distances between cores, and minimizing crosstalk between cores [46];

(2) Optimization of few/multimode multi-core structure: the number of cores and modes in multi-core fiber can be further optimized to increase transmission capacity and bandwidth; by studying different core arrangements and optimizing the spacing between cores, a more efficient few/multimode multi-core structure can be achieved [4];

(3) Novel coupling devices: developing more advanced multi-core fiber connectors and connection technologies to reduce insertion loss and reflection loss, thereby improving transmission efficiency and reliability [47];

(4) Compatibility and standardization: further advancing the compatibility and standardization of multi-core fiber to ensure seamless integration and interoperability of multi-core fiber products from different vendors, promoting the widespread application and market development of multi-core fiber.

These improvement directions in multi-core optical fiber technology will broaden its potential for long-distance, high-capacity communication applications, meeting the communication demands in various scenarios. This marks the fourth stage of the modernization, engineering, and commercial development of multi-core optical fibers.

3. Application of Multi-Core Optical Fibers in Sensing Networks and the Laser Field

In addition to the inherent characteristics of optical fibers, multi-core optical fibers possess unique features such as multi-channel transmission, high integration, spatial flexibility, resistance to interference, and multifunctionality. These attributes not only provide multi-core optical fibers with more flexible and efficient transmission capabilities in the field of communication, where they have become a hot topic in research and practice, covering various aspects, but also simultaneously opens up broader prospects for applications in other fields. This extensive range of applications propels the continuous development of multi-core optical fiber technology and contributes to the maturity of its fabrication techniques.

In the sensing domain, multi-core optical fibers leverage their multi-channel transmission capability to simultaneously measure various physical quantities. When combined with distributed sensing technology, they achieve more sensitive sensing performance, longer sensing distances, and a broader sensing range, offering an ideal platform for optical sensing. In the laser field, the high integration and flexibility of multi-core optical fibers make them an ideal choice for designing lasers and laser systems.

3.1. Application of Multi-Core Optical Fibers in Sensing Networks

Multi-core optical fiber sensing can be divided into point sensing and distributed sensing. In multi-core optical fiber point sensing, each channel can be used to measure a specific physical parameter at a particular position. By introducing different sensing mechanisms into different channels of the optical fiber, it can be employed to construct Fabry–Perot [48–55], Michelson [56–60], and Mach–Zehnder [61–76] interferometers, allowing independent measurements of physical parameters at specific locations. This enables real-time monitoring and perception of changes in physical parameters such as refractive index [56,57], temperature [48,69–73], bending [51,61,62,77], and strain [50,63–65]. The multi-channel nature of multi-core optical fibers can also facilitate the measurement of multiple physical parameters [52–54,66–68,74].

Conversely, multi-core optical fibers distributed sensing utilizes distributed technologies such as Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR). It relies on the distributed sensing technique based on the backscattered light within the cores of the multi-core optical fiber, covering the entire length of the optical fiber. Each channel simultaneously measures physical parameters at multiple positions. This continuous monitoring method is suitable for scenarios requiring real-time assessment of the overall system performance, making it applicable to a wide range of engineering applications such as oil well monitoring, geological exploration, pipeline safety monitoring [78–83], and aerospace applications [84–88] like wing monitoring and inertial navigation, as well as medical applications like medical robots and minimally invasive interventions [89–93]. The parallel channel structure of multi-core optical fibers provides an ideal platform for distributed sensing, allowing a single optical fiber to achieve efficient measurements at multiple points or along the entire length. When incorporating fiber grating structures [92–100], high sensitivity and high-resolution sensing can be achieved.

3.1.1. Engineering Applications

In 2002, the research team led by Araújo F.M. [101] fixed three optical fibers with Bragg grating structures in a sheath, as shown in Figure 3. This setup was used to measure curvature radii in different directions, achieving the monitoring and measurement of object shapes.

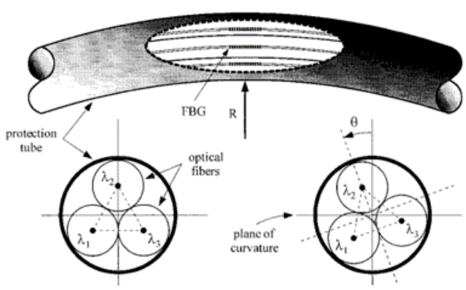


Figure 3. Geometry of the sensing head proposed by Araújo. F. M. et al. [101].

In 2006, the team led by Flockhars G.M.H. [62] confirmed that the use of multi-core optical fibers can also achieve monitoring and measurement of object shapes. Theoretically, three non-collinear measurement points are sufficient to reconstruct three-dimensional shapes. Therefore, as shown in Figure 4, whether it is a bundle of three fibers [102], multi-core fiber [89], or three fibers attached to flexible materials [103], they can be attached to objects of different shapes and sizes using flexible auxiliary tools. This allows them to adapt to surfaces with different curvatures and bends, maintaining good contact and close fitting. They can effectively track changes in the shape of the monitored object and provide accurate measurement data. The anti-electromagnetic interference and high chemical stability of multi-core optical fibers ensure their reliability during long-term monitoring, guaranteeing ease of installation and the effectiveness of shape tracking. This enables continuous, dynamic, and direct tracking of object shape information and position characteristics, providing important insights and methods for three-dimensional shape sensing and perception.

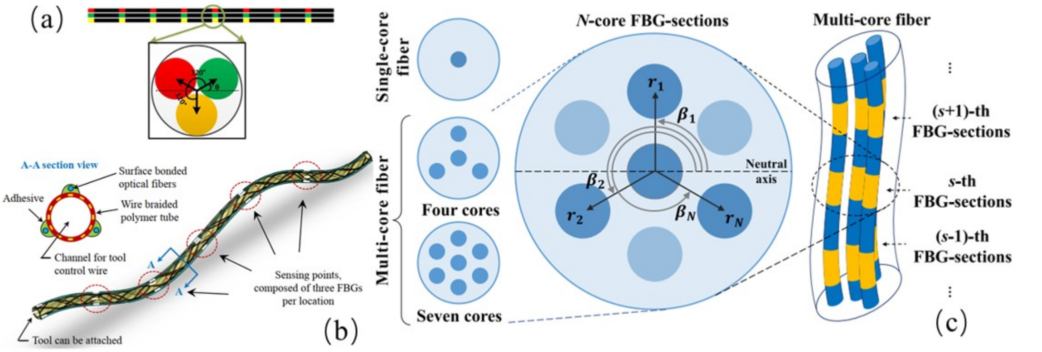


Figure 4. Possible geometrical configurations of optical fiber shape sensors: (**a**) bundle of three fibers [102]. (**b**) three fibers attached to flexible materials [103]. (**c**) multi-core optical fibers [89].

Compared to the structure of bundled fibers and three separate fibers, multi-core optical fibers require less space. multi-core optical fibers with an intermediate core can sense torsion by comparing the strain between the edge cores and the central core. Additional cores ensure redundancy in measurements and improve accuracy. In 2012, the team led by Lally E.M. [84] confirmed this concept, as shown in Figure 5, which includes a cross−sectional view of a four-core fiber and the strain response data collected from each core in response to external curvature. This approach frees researchers from the constraints of manually creating shape sensors and allows for direct adoption of multi−channel multi-core optical fibers for three-dimensional shape perception [80,104].

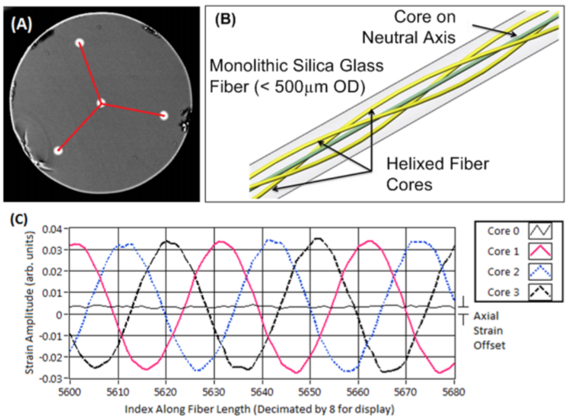


Figure 5. Illustration of shape sensing using helixed multi-core optical fiber: (**A**) SEM micrograph of shape sensing fiber, sensing triad in red. (**B**) Illustration of helical cores along length of fiber. (**C**) Typical four-core strain response to external curvature [84].

The ultimate goal of multi-core fiber shape sensing is shape reconstruction for monitoring in engineering applications. The key lies in the shape reconstruction algorithm.

Since it was first proposed, the three-dimensional shape sensing technology of multi-core optical fibers has been continuously updated and iterated. In 2012, the team led by Moore J.P. [105,106] proposed an improved algorithm for spatial three-dimensional shape reconstruction, known as the Frenet-Serret equations. The system of equations involves three main vectors: the tangent vector, the normal vector, and the binormal vector obtained by cross-multiplying the tangent and normal vectors. These three vectors form a set of orthogonal unit vectors used to describe the geometric features of the multi-core fiber path, including curvature, torsion, and direction. The algorithm reconstructs complex three-dimensional shapes using a continuous parameterization method, validating the feasibility of shape reconstruction for multi-core optical fibers around objects.

In 2018, the team led by Roesthuis R.J. proposed another method for reconstructing three-dimensional shapes using the Homogeneous Transformation Matrix Equation [107]. Generally, under equal arc length intervals, the reconstruction performance of the Homogeneous Transformation Matrix equation is expected to outperform the Frenet-Serret equations. However, since the homogeneous transformation matrix involves calibrating coordinate systems, its use is more complex compared to the Frenet-Serret equations. Nevertheless, the reconstruction errors of the Homogeneous Transformation Matrix equation do not undergo cumulative amplification, giving it an advantage in long-distance sensing. Conversely, the Frenet-Serret equations are advantageous due to their convenient usage. After simple optimization improvements, their reconstruction error performance can approach that of the Homogeneous Transformation Matrix. Currently, the Frenet-Serret equations remain the most widely studied reconstruction algorithm, and a detailed comparison of the two algorithms can be found in the research conducted by Paloschi.D and colleagues [108].

In 2020, the team led by Al-Ahmad O. [109] made further improvements to the reconstruction algorithm based on the Frenet-Serret equations and conducted experimental validation, achieving better accuracy and stability. In the same year, Jin J. [110] proposed a method for correcting calculated strains based on the Frenet-Serret equations. This method can be used to correct axial strain errors, specifically errors [111,112] induced by the twisting of the fiber itself, thereby enhancing the accuracy of fiber shape sensing.

In 2021, the team led by Chen Z. [83] reconstructed a complex 3D shape of a groove with a variable curvature radius (5 cm to 100 cm) using a three-core optical fiber, as shown in Figure 6. The root-mean-square error of the curvature radius for the reconstructed 3D spatial curve was 7.2 mm.

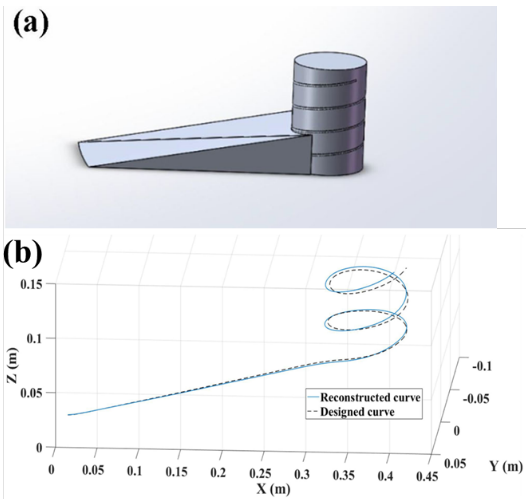


Figure 6. Structural monitoring model: (**a**) 3D phantom contained a groove with a variable curvature radius of 5 cm to 100 cm, and (**b**) reconstructing results of the 3D phantom contained a groove with variable curvature radii of 5 cm to 100 cm by 3D printing. The solid line is the reconstructed 3D curve. The dashed line is the designed 3D curve SEM micrograph of the shape [83].

However, the practical application of multi-core optical fiber distributed three-dimensional shape sensing technology still faces several challenges. One such challenge is how to accurately position and calibrate the optical fiber sensors to ensure the accuracy and reliability of the measurement results. In addition, it is necessary to develop data processing and analysis methods that can adapt to different types of structures and operating conditions, enabling effective monitoring and analysis of structural shapes and deformations. Despite some challenges in engineering applications, multi-core optical fiber distributed three-dimensional shape sensing shows potential in areas such as building condition monitoring and precision operation of mechanical devices [113,114]. With ongoing technological advancements and accumulated engineering experience, it is anticipated that the engineering applications in this field will further develop and mature.

3.1.2. Medical Applications

In the field of medicine, minimally invasive intervention surgery is a surgical method that involves using small incisions or vascular catheterization to diagnose and treat patients using tools such as catheters and guide wires [115,116]. Compared to traditional open surgery, it offers advantages such as minimal trauma, fast recovery, and fewer complications. In minimally invasive intervention surgery, the navigation system plays a crucial role. The navigation system utilizes real-time imaging technology to accurately locate and display the patient's anatomical structure and the position of surgical instruments, helping the surgeon accurately locate the lesion and guide the operation. It also monitors the position and posture of the surgical instruments, ensuring the accuracy and safety of the surgical procedure. The navigation system typically consists of three main components: imaging system, localization system, and surgical planning and navigation software. The imaging system is used to obtain images of the patient's anatomical structure, such as ultrasound imaging, CT (Computed Tomography), MRI (Magnetic Resonance Imaging), etc. The localization system utilizes special sensors and instruments to obtain the position and directional information of the surgical instruments inside the patient's body. The surgical planning and navigation software integrates and processes the imaging data and localization information, providing an intuitive navigation interface to assist the surgeon during the operation. However, despite the application of ultrasound imaging in minimally invasive intervention surgery, its resolution is limited. CT imaging equipment is fixed, less flexible, and can cause radiation damage to patients or doctors. Furthermore, although MRI has various advantages, its imaging rate is low and it is incompatible with certain electromagnetic materials. At the same time, the reconstruction speed of computed tomography imaging and magnetic resonance imaging is slow, and the reconstruction time for computed tomography imaging usually takes several tens of seconds. Due to these disadvantages, a single image−guided approach cannot meet clinical needs.

In 2010, the team led by Park Y.L. [117] proposed the use of a biopsy needle compatible with MRI, equipped with three optical fibers containing Bragg gratings, as shown in Figure 7. This needle was designed to measure the bending deflection of the needle during tissue insertion, aiming to minimize positioning errors and surgical complications. Subsequent research also explored the use of fiber bundle Bragg gratings for localization reconstruction [118–125], indirectly suggesting potential applications of multi-core optical fibers in the medical field.

Compared to traditional bundles of individual optical fibers used in the medical field, multi-core optical fibers have a smaller size, allowing for more convenient integration into miniature medical devices. Additionally, in multi-core optical fibers, the relative distances between cores remain constant, ensuring consistent inter-core temperatures. These characteristics make multi-core optical fibers more advantageous than single-core fibers. Their emergence provides doctors with more comprehensive, efficient, and safe tools, driving the development of minimally invasive medical technology and delivering improved treatment outcomes and recovery experiences for patients.

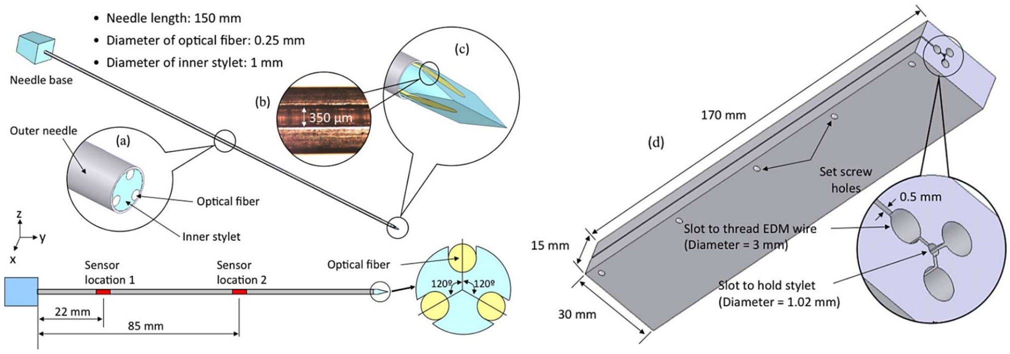


Figure 7. Prototype design with modified inner stylet incorporated with three optical fibers. Three identical grooves at 120° intervals are made on the inner stylet to embed optical fibers with FBGs along the needle length. (**a**) Midpoint cross section. (**b**) Magnified view of an actual groove. (**c**) Tip of the stylet. (**d**) Fixture design for EDM parallel grooves in the biopsy needle stylet [117].

In 2019, Khan F. and others [97] proposed a flexible medical instrument based on multi-core fiber Bragg gratings (FBGs) capable of shape reconstruction in three-dimensional space, as shown in Figure 8. In theory, a single multi-core optical fiber with FBG sensors is sufficient for reconstructing three-dimensional shapes. However, they utilized four multi-core optical fibers, introducing redundant fibers to enhance the reliability of the sensing system in case of a failure in a single fiber Bragg grating sensor.

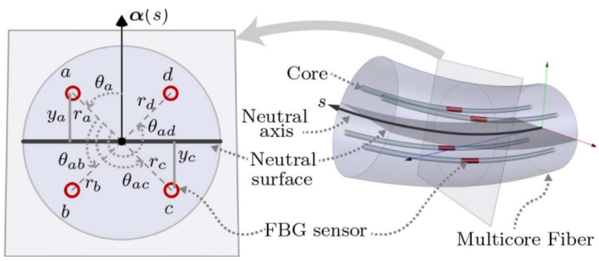


Figure 8. multi-core optical fiber with one set of fiber Bragg grating (FBG) sensors [97].

Since then, this research has spurred other scientists to delve deeper into multi-core optical fiber sensing technology [88–92]. In subsequent explorations, research teams have tirelessly worked towards developing new techniques to mitigate errors caused by environmental disturbances and optical fiber twists.

In summary, the advantages of multi-core optical fiber for three-dimensional shape sensing, such as its high flexibility and chemical inertness, enable it to adapt to complex anatomical structures and confined operational spaces. The multi-core structure, with cores collectively encapsulated, allows for integrated "multi-functional" capabilities. For instance, one core can transmit image data elements, another can transmit laser energy elements, and additional cores can accommodate communication, illumination, and other elements. This facilitates functions such as image guidance, therapeutic operations, and illumination, thereby enhancing surgical efficiency and accuracy. As depicted in Figure 9, with the continuous advancement of technology, the application prospects of multi-core optical fiber in the medical field will further expand [91,92,97,117–123], including applications in endoscopic surgery, neurosurgery, cardiovascular intervention, and cardio-pulmonary navigation.

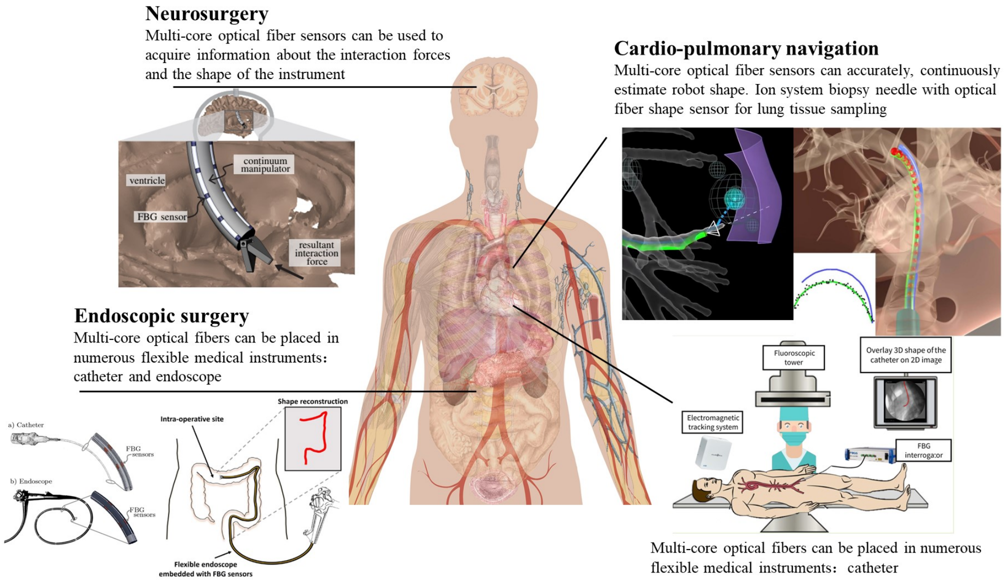


Figure 9. The potential applications of multi-core optical fibers in medicine [91,92,97,121–123].

3.1.3. Aerospace Applications

In 2012, Lally E.M.'s team [84] verified that multi-core optical fibers can be used to monitor shape changes in flexible components of high-performance aerospace applications, such as aircraft wings, composite wind turbine blades, and suspension bridges. Figure 10 shows the fiber layout adhered to a metal thin plate structure to monitor its shape changes, providing valuable data for the design, testing, and operation of intelligent flexible structures.

The Interferometric Fiber Optic Gyroscope (IFOG) serves as a cornerstone for inertial measurement and attitude reference applications, and stands as one of the most successful examples in the history of fiber optic sensing technology. It finds extensive usage in the fields of aerospace, missile guidance, and seismic monitoring. The core of this sensor is a long-distance optical fiber loop, which converts rotational motion into optical phase shift parameters, thereby achieving interference-based detection of rotation rate. The current IFOG optical fiber loops consist of standard single-mode or polarization-maintaining fibers. However, recent advancements in multi-core fiber technology suggest the advent of a new generation of IFOGs, offering enhanced precision and performance. multi-core optical fibers with ultrahigh signal density can provide substantial performance gains and dramatically reduce the size of the sensor. Moreover, these multi-core optical fibers can facilitate spatially coupled common phase optical paths with high flexibility, which can be employed to simplify traditional fiber winding processes and error correction architectures, thereby opening up new possibilities for IFOG design [87,88].

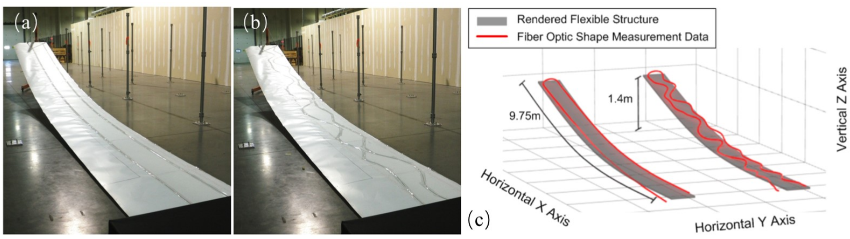


Figure 10. Setup of structural monitoring experiment, images of actual flexible test article with shape sensing fiber attached in (**a**) simple U-shaped path and (**b**) convoluted path. (**c**) Orthographic view of measured fiber optic shape data at 1.4 m deflection overlaid with rendering of test structure (based on physically-measured data) [84].

This viewpoint has been validated in the seven-core fiber gyroscope developed by Mitani S.'s team in 2019 and Taranta. A's team in 2020, as shown in Figure 11. The signal light path begins with the light source passing through an Integrated Optics Circuit (IOC) Y-waveguide phase modulator, resulting in the output of highly polarized light signals. These signals then pass through the multi-core fiber loop, establishing the optical path of the seven-core fiber gyroscope.

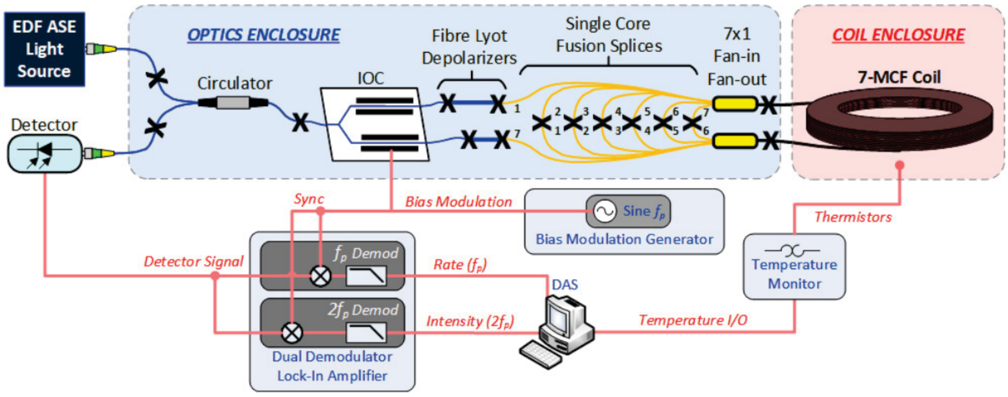


Figure 11. multi-core IFOG Testbed Diagram [87].

In summary, multi-core optical fibers enable the transmission of multiple channels, with each channel capable of independently sensing different physical parameters. By introducing appropriate sensing elements or materials into different fiber cores [72,73,126], simultaneous monitoring of multiple parameters, such as temperature, pressure, strain, and humidity, can be achieved. This ability for multi-parameter sensing provides great convenience for real-time monitoring and perception of changes in multiple physical parameters within the environment. The application of multi-core optical fibers in the field of sensing continues to expand and innovate, offering more efficient, sensitive, and reliable solutions for real-time monitoring, detection, and diagnostics. With further technological advancements, the prospects for the application of multi-core optical fibers in the sensing field will continue to broaden, bringing forth more opportunities for innovation and development in engineering monitoring, aerospace, medicine, and other domains.

3.2. The Application of multi-core Optical Fibers in Lasers

Compared to single-core optical fiber lasers, multi-core optical fiber lasers possess a larger effective mode field area, which is advantageous for enhancing the output power of the laser beam. The various fiber cores within the multi-core optical fiber laser are closely connected, forming a direct super-mode conduction. Due to the fixed distances between the fiber cores, the phase difference between the cores is locked, while the discrete distribution of the cores facilitates mode coupling. Therefore, multi-core optical fiber lasers can achieve high-power laser output and provide an alternative possibility for high-power output of fiber lasers [127]. multi-core optical fiber lasers are a special type of laser that utilize the structure of multi-core optical fibers to realize multiple independent laser channels, allowing for the adjustment of laser beam power, mode, and direction as needed [128–132].

In multi-core optical fiber lasers, multiple fiber cores are arranged in parallel, each capable of transmitting an independent laser beam. These beams can be output simultaneously or controlled and adjusted separately, enabling multi-channel laser output [133–139]. Figure 12 illustrates the optical path diagram of a fiber laser constructed using multi-core optical fibers. By integrating multiple laser channels within the same fiber, the size and weight of the laser device can be significantly reduced. multi-core optical fiber lasers, integrated with their navigation and imaging systems, are more suitable for minimally invasive surgeries and endoscopic operations in the medical field. For example, in laser surgery, multi-core optical fiber lasers can output laser beams while simultaneously providing navigation and positioning for cutting, coagulation, and irradiation, among other therapeutic operations. In laser therapy, the multiple channels of multi-core optical fiber lasers can be used to transmit lasers of different wavelengths separately, thereby achieving specific treatment effects.

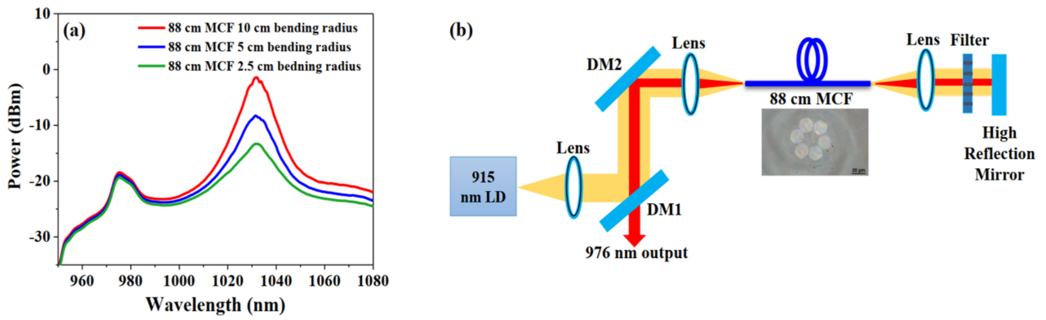


Figure 12. (**a**) ASE spectra of 88 cm length MCF with different bending radius. (**b**) Configuration of 976 nm fiber laser based on 88 cm length MCF [136].

Multi-core optical fiber lasers have significant application value in the medical field. Their multi-channel output, compact design, and adjustability make them powerful tools for various laser surgeries and treatment applications, offering doctors more choices and flexibility while improving treatment effectiveness and patient safety.

In summary, the advantages of multi-core optical fibers in the field of sensing are more pronounced compared to their applications in communication. This is primarily manifested in their multi-channel structure, which supports more complex and diverse sensing applications. To facilitate the rapid development of multi-core optical fiber sensing technology, here are some potential directions for improvement:

(1) Multimode Sensing: Fully utilize the multi-channel structure of multi-core optical fibers and develop technologies that support multimode sensing. By modulating and analyzing the modes of different channels, it is possible to achieve more flexible and versatile sensing applications, enhancing the information acquisition capability of sensing systems;

(2) High Sensitivity Sensing: Leverage the sensitivity of multi-core optical fibers to external environmental changes to develop sensors with higher sensitivity. By optimizing the fiber materials and structures, such as enhancing backscattered light signals, it is possible to improve the detection sensitivity to weak signals. This is applicable to various high-precision measurement sensing applications, such as temperature, pressure, humidity, etc.;

(3) Multifunctional Integrated Sensing Systems: Integrate different functional sensors into multi-core optical fibers to form multifunctional sensing systems. Through the thoughtful design of channel structures, simultaneous monitoring of multiple parameters can be achieved, enhancing the overall performance and practicality of sensing systems;

(4) Holographic Sensing Technology: Exploit the multi-channel nature of multi-core optical fibers to develop holographic sensing technology. This could involve using multiple channels for recording and reconstructing holographic images, enabling more comprehensive information extraction, especially for measuring parameters related to three-dimensional shapes and deformations;

(5) Embedded Sensing Applications: Integrate multi-core optical fibers into materials or structures for embedded sensing applications. This can be utilized for real-time monitoring of structural health and material properties, holding significant potential for applications in engineering structures and materials science;

(6) real-time Data Processing and Feedback: Develop technologies for real-time data processing within multi-core optical fiber sensing systems, enabling immediate feedback and processing of sensing data. This will enhance the response speed and practicality of sensing systems.

In conclusion, the directions for improving multi-core optical fiber sensing technology encompass aspects such as sensing modes, sensitivity, integrated systems, holographic technology, embedded applications, adaptation to extreme environments, and real-time data processing. Research and innovation in these directions are expected to facilitate the broader and more in-depth application of multi-core optical fiber sensing technology across various real-world scenarios.

4. Manufacturing Techniques for multi-core Optical Fibers

multi-core optical fibers have brought new opportunities to sensing applications and communication. However, they are still in the early stages of development and need to overcome a series of technical, standardization, and application challenges to realize their extensive and profound application. As a core component, the intrinsic characteristics of multi-core optical fibers are crucial for their successful application. In the continuous pursuit of technological innovation, it is essential to delve into the performance and manufacturing technology of multi-core optical fibers. This understanding will enable us to better leverage the advantages of multi-core optical fibers and address various challenges that may arise in practical applications. While striving for technological excellence, it is equally important to maintain sensitivity to the manufacturing technology of multi-core optical fibers to adapt to evolving demands and challenges.

Researchers have gained a clear understanding of many fundamental theories regarding multi-core optical fibers. However, there remain several important issues that have not been fully addressed for long-distance optical fiber communication, integrated fiber optic devices, and specialized sensing applications. These issues include attenuation, crosstalk between cores, differential bending loss caused by variations in core positions, degradation of external cores, and precision in core arrangement within multi-core optical fibers.

Different applications place varying degrees of importance on the parameter specifications of multi-core optical fibers, as shown in Table 1, the greater the number of pentagrams represents the greater importance. For communication purposes, parameters such as transmission capacity, distance, attenuation, crosstalk, and effective area are crucial. Sensing applications require shorter fiber lengths, demodulation requirements, and high sensitivity, with a relatively higher emphasis on crosstalk and bending losses.

Table 1. Importance of Key Parameters for Different Applications of multi-core Fibers.

Application	Importance of Key Parameters				
	Attenuation	**Crosstalk**	**Bend Loss**	**Effective Area**	**Core-to-Core Distance Precision**
Optical Communication	★★★	★★★	★★★	★★★	★
Optical Sensing	★	★★★	★★★	★	★
Fiber Lasers	★★	★★	★★★	★★★	★

The urgent need for long-distance information transmission led to the use of quartz glass by Corning in 1984 for experiments [140]. The outside vapor deposition(OVD) process, described in US Patent 3711262, was used to achieve the low-loss circular cross-section glass medium fiber waveguide concept proposed by Keck in 1966 [141]. Thus, optical fibers made their debut, capable of carrying 65,000 times more information than copper wires and transmitting signals to destinations a thousand miles away. The manufacturing technology for quartz glass fibers gradually matured, resulting in fibers with low attenuation, large bandwidth, low cost, and resistance to electromagnetic interference. The thinking behind fiber manufacturing also broadened, leading to the development of various commercial production methods for quartz glass fibers [142], including modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), vapor axial deposition (VAD), and plasma chemical vapor deposition (PCVD). The rod-in-tube (RIT) [143] method transformed into rod-in-cylinder (RIC) as fiber preforms increased in size.

The earliest method for manufacturing multi-core optical fibers was jointly proposed by France Telecom and Alcatel. They used the FCVD (fluorine-doped chemical vapor deposition) process to manufacture the cladding tube and core rod. These components were then combined using grinding and stacking methods to successfully produce a four-core single-mode fiber [12] with a length of over 100 km. This marked the beginning of practical, commercialized multi-core optical fibers.

The manufacturing methods for multi-core optical fibers can be summarized as shown in Figure 13. Based on the design of the fiber's geometry and optical characteristics, various high-precision chemical vapor deposition methods are used to produce core rods, cladding rods, and auxiliary rods. These prepared rods are then combined using methods such as grinding [44,144,145] and stacking [46,146–153], rod drilling [45,154–157], and other improved and novel techniques [158–171]. The resulting multi-core fiber preform is then drawn into a multi-core fiber through a series of processes.

During the fiber manufacturing process, the choice of materials [172] and methods is determined based on the designed geometry and optical parameters. Researching the manufacturing techniques for multi-core optical fibers is beneficial for improving fiber quality, enhancing transmission capacity, and expanding the applications of multi-core optical fibers. It is worth mentioning that multi-core optical fibers are not only made from quartz glass but also from multi−component glasses.

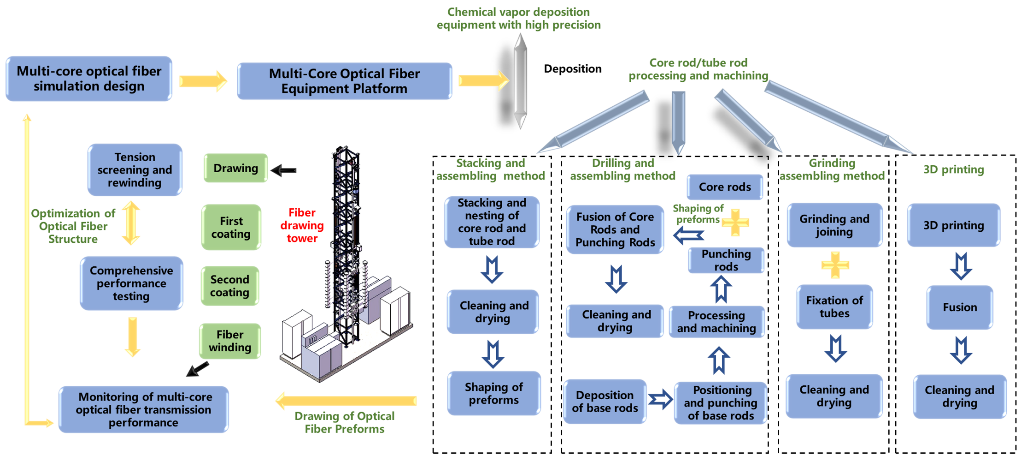


Figure 13. Simplified flowchart of multi-core fiber manufacturing process.

In 1999, Dorosz.J employed a modified multicrucible (MMC) technique to fabricate multi-component glass multi-core optical fibers [173]. Figure 14 depicts the modified multi-crucible cross-section, where crucible 1 is used to separate the core glass from the cladding glass. The inner crucible 1 and middle crucible 2 are connected by a permanent connecting tube 4, which prevents the core glasses from adhering to each other, forming an intermediate core and avoiding deformation. The middle crucible 2 contains the core glass, and the number of nozzles matches the number of cores designed for the multi-core fiber. Altering the shape of the nozzles can also change the shape of the surrounding cores. The molten glass in the outer crucible 3 constitutes the cladding of the multi-core fiber. The core glasses are injected into the cladding glass through the nozzles at the bottom of the inner crucible, and the combined glass flows out of the outer crucible through the bottom nozzle 5, forming a non-mixed glass body. The glass body is then drawn and coated to produce a multi-core fiber. Figure 15 illustrates a cross-section of the fabricated multi-core fiber.

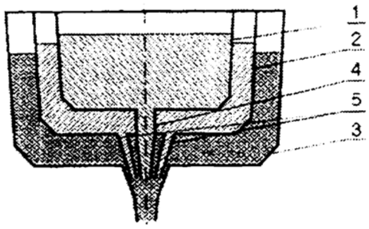


Figure 14. Three−crucible geometry for manufacturing MMC multi-core optical fibers (internal crucible separation process) [173].

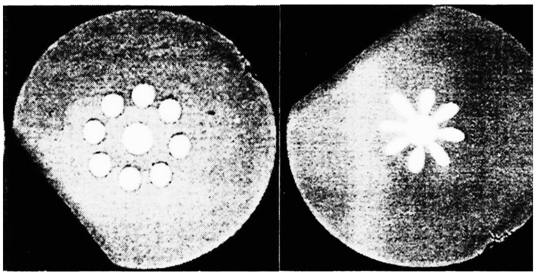


Figure 15. MMC multi-core optical fibers manufactured by internal crucible separation process [173].

However, the improved crucible technique introduced a significant amount of impurities to the multi-component multi-core optical fibers, resulting in uncontrollable fiber attenuation. Moreover, the geometric precision relies on the dimensional accuracy of the crucible nozzles. The development of the crucible technology lags far behind the growth rate of optical fiber demand in communication applications. Additionally, the high absorption coefficient of the multi-component materials leads to further attenuation in the communication wavelength band. Therefore, the fabrication of communication-grade multi-core optical fibers using crucible techniques has not been extensively investigated and industrial production has not been achieved.

4.1. Tube-in-Rod Grinding Assembling Technique

In 1994, France Telecom utilized the FCVD technology to prepare individual core rods, which were then finely polished on their side surfaces to achieve the desired angles for interconnection. These rods were then assembled by joining them together, secured with a quartz sleeve, and subjected to high-temperature heating for fusion. Throughout the entire process, it was crucial to ensure that the preform rods were clean and dry. Finally, the multi-core fiber preform rod was drawn. Figure 16 illustrates the cross−section of a four-core fiber preform rod assembly [144,145].

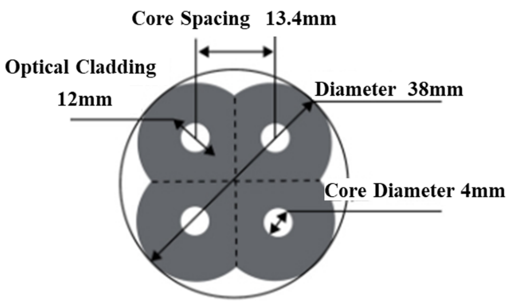


Figure 16. Cross−section of a four−core preform rod assembly [144].

In 2000, Peterk.P from the Radio Engineering and Electronics Research Institute of the Czech Academy of Sciences employed the polishing and fusion splicing technique to fabricate dual-core fibers, as shown in Figure 17 [44].

As the number of fiber cores increased, it became necessary to finely polish the side surfaces of multiple single-mode fiber preform rods to enable their assembly into a multi-core fiber preform rod. This process was complex and varied depending on the arrangement of the fiber cores. The shape of the core rod's cold-worked grinding also differed, making the process intricate and costly. Therefore, it was not suitable for preparing multi-core optical fibers with a large number of cores. In particular, the splicing scheme for "non-circular symmetric" structured multi-core optical fibers was even more complicated and challenging to achieve with automated control. Consequently, this multi-core fiber fabrication technique did not receive widespread attention.

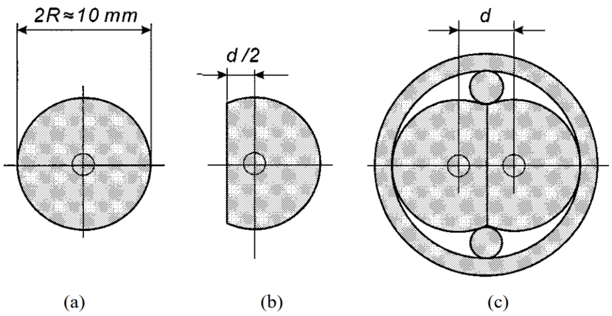


Figure 17. Steps of a twin-core preform preparation using the conventional method (**a**) Cross-section of single-core preform of typically 10 mm diameter. (**b**) Preform ground on one side. (**c**) Composite twin-core preform [44].

4.2. Tube-in-Rod Stacking and Assembling Technique

The tube-in-rod stacking and assembling technique is a commonly used and mature method for fabricating multi-core optical fibers, as depicted in Figure 18 [149]. In step (1), multiple fiber preform rods, prepared using chemical vapor deposition, and gap-filling rods, typically composed of quartz glass, are combined. The gap-filling rods are used to fill the spaces between the fiber preform rods. The manufacturing process requires various procedures such as cleaning, polishing, drying, and precise pressure (or vacuum) control to prevent the formation of bubbles inside. In step (2), the prepared fiber preform rods and gap-filling rods are stacked according to the designed multi-core fiber structure and inserted into a quartz sleeve together. In step (3), the stacked structure is fused using a glass lathe while simultaneously applying vacuum to complete the fabrication of the multi-core fiber preform rod. Finally, in step (4), the multi-core fiber preform rod is drawn to produce the final multi-core fiber product.

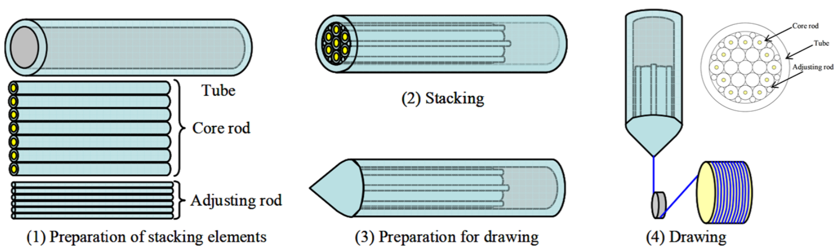


Figure 18. Fabrication process of MCF by stack and draw [149].

In 2011, Katsunori I. et al. utilized the tube-in-rod stacking and assembling technique to fabricate a hexagonal seven-core single-mode fiber [147] with a cladding diameter of 141 µm, as shown in Figure 19. The spacing between the fiber cores was 40 µm, and the maximum fiber attenuation was 0.444 dB/km @1550 nm. The maximum crosstalk for a 2 km transmission distance was −17 dB.

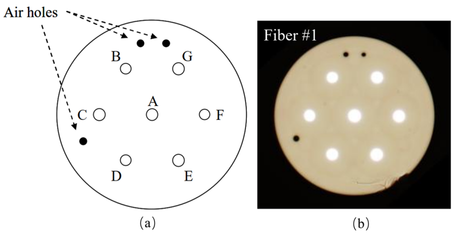


Figure 19. seven-core optical fiber: (**a**) Cross-section of designed fiber with air holes as markers. (**b**) Cross-section of fabricated fibers [147].

The method of tube-and-rod nesting and stacking combination is highly dependent on the dimensional matching of the fiber preform rod and the gap-filling rod for the alignment accuracy and spacing accuracy of each fiber core. However, during the stacking process, unavoidable gaps will be created, resulting in errors in the alignment of each fiber core, fiber core deformation, non-uniformity, and fiber bubbles. Additionally, the fiber preform rod used in the stacking process is subject to compression and contamination from airborne particles. Therefore, the stacking environment of the fiber preform rod and the gap-filling rod is particularly important in the preparation process of the tube-and-rod nesting and stacking combination method.

In 2013, Ishida I. et al. studied the effect of spatial particle concentration during the stacking process on the attenuation of 12-core optical fibers using the tube-and-rod nesting and stacking combination method [149]. The study showed a strong correlation between the attenuation of 12-core optical fibers and spatial particle concentration. In an environment with low particle concentration during the preform rod stacking process, the surface cleanliness of the fiber preform rod and the gap-filling rod is higher, resulting in smaller attenuation of the multi-core optical fibers prepared. Figure 20 illustrates the relationship between the attenuation of 12-core optical fibers and spatial particle concentration.

By replacing the gap-filling rod with a single-mode fiber preform rod or increasing the diameter of the preform rod, the tube-and-rod nesting and stacking combination method can be used to fabricate 16-core [174], 19-core [175–178], 22-core [19], 30-core [179], 36-core [180], and even more core-count [181–185] multi-core optical fibers. The tube-and-rod nesting and stacking combination method can also be used to prepare rectangular core [186–189] multi-core optical fibers using air-core. In summary, the preparation scheme is flexible, making it a highly regarded method for fabricating multi-core optical fibers. Table 2 shows the characteristics of multi-core optical fibers prepared using the tube-and-rod nesting and stacking combination method in recent years at a wavelength of λ = 1550 nm.

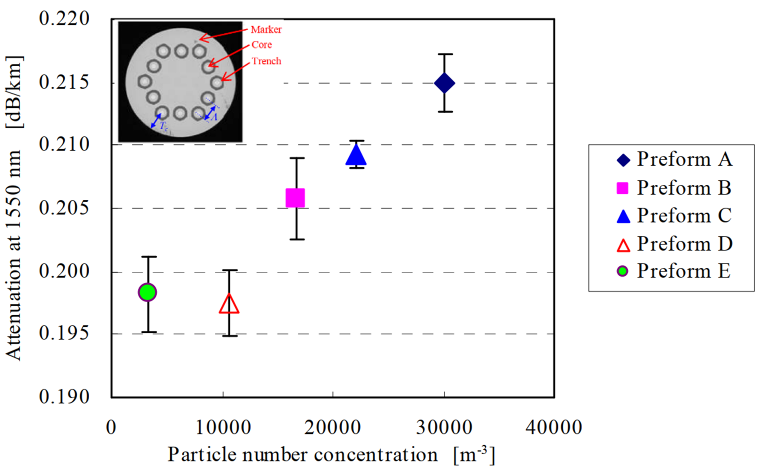
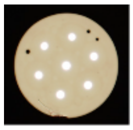
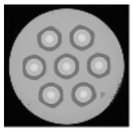
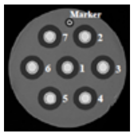
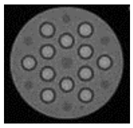
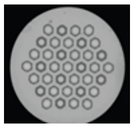


Figure 20. Particle number concentration dependence of attenuation [149].

Table 2. Characteristics of multi-core optical fibers prepared using the tube-and-rod nesting and stacking combination method at a wavelength of λ = 1550 nm.

Year	Core Count	Attenuation (dB/km)	∣Crosstalk∣	Fiber Core Spacing	End Face	Reference
2010	7	0.25	17 dB/2 km	40 µm		[147]
2011	7	0.21	35 dB/100 km	38.3 µm		[148]
2011	7	0.171	37.7 dB/100 km	45 µm		[46]
2014	12	0.2	50.6 dB/100 km	44.5 µm		[153]
2016	16	0.2	40.5 dB/55 km	37.5 µm		[174]
2017	37	0.241	20 dB/1000 km	29.1 µm		[182]

4.3. Combination Method of Tube-and-Rod Drilling

The process of drawing preforms for multi-core fiber using the tube-and-rod nesting and drilling method is similar to that of the tube-and-rod drilling method. The main difference lies in the preparation of the multi-core fiber preform. In the tube-and-rod drilling method, the drilling process determines the position of the core area through hole arrangement. Therefore, the drilling process is a key step in achieving accurate positioning and high-precision layout of the multi-core fiber preform. Mechanical drilling is mainly used in the drilling process of multi-core optical fibers, which incurs higher time costs and lower fault tolerance. Mechanical drilling is a form of glass cold working, a process that changes the shape and surface condition of glass products through mechanical methods without heating. Therefore, micro-cracks and high surface roughness are inevitable during the drilling process, which affects the attenuation performance of multi-core optical fibers. As the number of cores in multi-core optical fibers increases, the number of drilling holes in preforms also increases. This leads to increased complexity and cost in the tube-and-rod drilling method. Mechanical drilling also involves issues such as precision of the CNC machine tool and limitations on drilling hole size based on the dimensions of the drilling rod and bit.

In 2007, Lousteau J. prepared a tri-core tellurite glass optical fiber using the combination method of tube-and-rod drilling [45]. After the continuous improvement of fiber preparation technology, the tube-and-rod drilling method gradually evolved into using MCVD, PCVD, and other vapor-phase deposition techniques, as shown in Figure 21 [149], which illustrates the steps of the tube-and-rod drilling method: (1) precise drilling on the rod using advanced equipment [154–157], followed by cleaning and polishing processes to maintain the cleanliness of the tube hole's interior; (2) inserting core rods, prepared using the same vapor-phase deposition technique, into the cleaned and dried tube holes to form a multi-core fiber preform; and (3) producing multi-core fiber products after the drawing process.

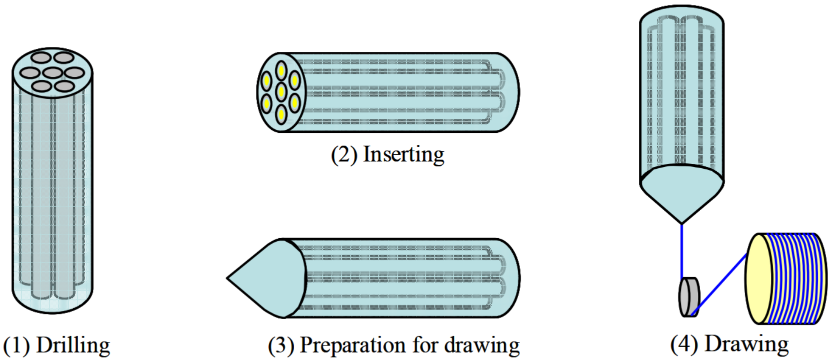
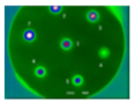


Figure 21. Fabrication process of MCF by drilling [149].

Currently, drilling processes with hole diameters below 3 mm are still under development, which limits the size of multi-core fiber preforms and affects the layout of multi-core fiber cores. Therefore, precision of the CNC drilling machine tool and dimensions of the drilling rod and bit in mechanical drilling are urgent issues to address. Referring to the laser drilling technique in the preparation method of photonic crystal fibers [190,191], which can achieve hole diameters of up to 0.8 mm with micrometer-level precision, it is believed that laser drilling will replace mechanical drilling in the near future. This will solve the problems of limited hole diameter size, poor positioning accuracy, and low surface damage in the tube-and-rod drilling method. It is worth mentioning that ultrasonic drilling [192] may also be one of the future directions for multi-core fiber drilling processes.

Table 3 shows the characteristics of multi-core optical fibers prepared using the tube-and-rod drilling method in recent years.

Table 3. Characteristics of multi-core optical fibers prepared using the tube-and-rod drilling method at λ = 1550 nm.

Core Count	Attenuation (dB/km)	∣Crosstalk∣	Fiber Core Spacing	End Face	Reference
7	0.19	76 dB/10 km	65 µm		[155]
7	0.25	35 dB/100 km	50 µm		[154]
7 cores 10 modes	0.25	50 dB/100 km	42 µm		[156]

4.4. Other Fabrication Techniques

The primary methods for fabricating multi-core optical fibers are the grinding and splicing method, the rod-in-tube stacking method, and the rod-in-tube drilling method, as previously discussed in this article. With the continuous cross-disciplinary development of optical fibers and other fields, the fabrication process of multi-core optical fibers has also been continuously updated and iterated. In recent years, researchers have introduced 3D printing technology for the fabrication of multi-core optical fibers [161–171], or have improved the rod-in-tube stacking method [158–160].

three-dimensional printing, also known as additive manufacturing, is a type of rapid prototyping technology. In 2015, Cook K., Canning J., and others proposed the use of 3D printing technology for the fabrication of air-hole preform rods for optical fibers [161,162]. Subsequently, it has gradually been used for the fabrication of single-mode fibers [163–167], photonic crystal fibers [168,169], and multi-core optical fibers [170,171]. The fabrication of multi-core optical fibers using 3D printing is based on the rod-in-tube drilling method. Firstly, 3D printing is used to produce an adapter sleeve to replace the rod-in-tube drilling, as shown in Figure 22. Then, the core rods and pure quartz auxiliary rods are inserted into the specially shaped quartz sleeve and covered with an outer jacket to form a multi-core optical fiber preform with micro-gaps.

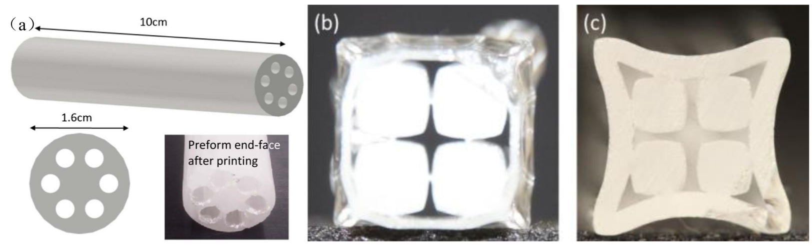


Figure 22. Optical fiber preform fabricated using 3D printing technology: (**a**) Illustration of fibre preform design [161]. (**b**,**c**) Lead-silica glass preform cross-section for the first (**b**) and second (**c**) iteration of die design [171].

The fabrication of multi-core optical fibers using 3D printing is a new direction proposed by scientists and has unprecedented advantages in terms of fabricating large-sized preform rods. However, there are still many challenges to overcome. For example, existing printing technologies mostly focus on printing polymer fibers, although there are also attempts to print quartz materials. However, ensuring the purity of printed quartz materials is difficult, resulting in insufficient purity of the preform rods and high loss of the drawn fibers. Therefore, the maturity of the fabrication technology for multi-core optical fiber preform rods used in long-distance communication needs to be improved. Moreover, the fiber cores and claddings of multi-core optical fibers require multiple doping materials, and switching materials during the printing process is a key challenge in the fabrication of fiber preforms. Once these problems are solved, fiber fabrication can be achieved solely through 3D printing, resulting in more flexible and diverse fabrication structures.

In 2017, Nozoe S. et al. proposed the technique of outer cladding deposition tube-and-rod stacking combination [158]. This method is essentially an improvement on the tube-and-rod nesting stacking method, with the main distinction being the absence of quartz tubing as a cladding fixing element in the outer cladding deposition tube-and-rod stacking combination method [159,160]. The OVD (Outside Vapor Deposition) method is instead employed to deposit the cladding layer, as illustrated in Figure 23.

The process involves the following steps: (1) Firstly, the prepared core rods and gap-filling rods are stacked according to the designed multi-core fiber end-face structure. (2) The stacked tube-and-rod structure is then extended with alignment rods at both ends to facilitate cladding deposition using the OVD method. After the cladding is deposited, the multi-core fiber preform is sintered. During this process, air holes are formed between the core rods due to the tension applied. Thus, the size of the air holes can be controlled by adjusting the diameter of the gap-filling rods and the deposition conditions of the OVD method. (3) The multi-core fiber is drawn into shape. The prepared four-core single-mode fiber with air holes has a core-to-core spacing of 40 μm. The maximum fiber attenuation is 0.19 dB/km @1550 nm, and the maximum crosstalk value is −30 dB/100 km. Compared to the multi-core fiber prepared using the tube-and-rod nesting stacking combination method, the crosstalk value is reduced by 5–10 dB in the outer cladding deposition tube-rod stacking combination method. Furthermore, the core deformation in the outer cladding deposition tube-and-rod stacking combination method is smaller than that in the original tube-rod nesting stacking combination method. The uniformity and core non-circularity are significantly improved, and the arrangement accuracy of the fiber end-face is close to that achieved with the tube-and-rod drilling method [159].

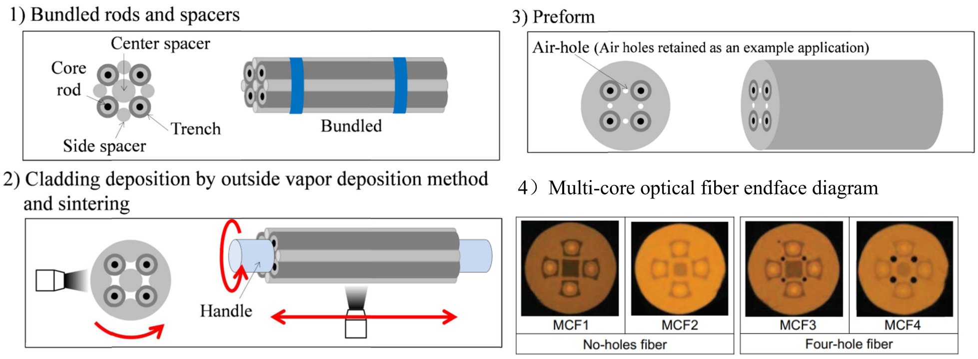


Figure 23. Schematic diagram of over-cladding bundled rods method [159].

4.5. Discussion and Prospects of Preparation Methods

The year 1994 marked the beginning of the commercialization of multi-core optical fibers. At that time, the basic method of tube-and-rod nesting stacking, as well as the grinding and splicing method for multi-core fiber preparation, had already been proposed. However, due to limited application demands and technological constraints, multi-core optical fibers were not widely prepared and applied between 1994 and 2010, and they remained in the theoretical development stage. Subsequently, as the transmission capacity of single-mode single-core fibers reached the Shannon limit, researchers began to explore solutions from the perspective of spatial division multiplexing, bringing multi-core optical fibers into their field of view. By this time, the development of tube-and-rod stacking technology and mechanical drilling technology had already met the requirements for multi-core fiber preparation, and multi-core optical fibers entered a period of rapid development starting from 2010. Figure 24 illustrates the development trend of multi-core optical fibers.

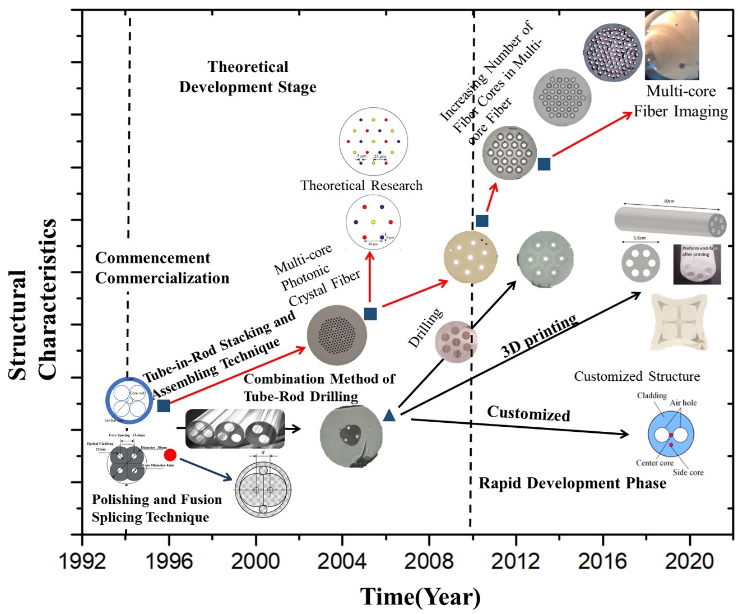


Figure 24. Development trends of multi-core optical fibers.

It can be observed that various methods have their own advantages and disadvantages. The tube-and-rod stacking and tube-and-rod drilling methods have achieved greater maturity and wider application, making them the preferred methods for multi-core fiber preparation. The tube-and-rod stacking method provides flexibility in multi-core fiber preparation and is suitable for multi-core optical fibers with a larger number of cores, as well as some small-diameter multi-core optical fibers with irregular cores. It is currently the most widely used method. However, it is slightly inferior to the tube-and-rod drilling method in terms of core eccentricity, uniformity, fiber bubbles, and precision of fiber end-face arrangement. Conversely, the drilling process in the tube-and-rod drilling method may limit the optical performance and preform size of multi-core optical fibers. This method is suitable for multi-core fiber preparation with a smaller number of cores and high precision in fiber end-face arrangement. There is still room for improvement in the drilling process, such as the use of laser drilling technology. It is worth mentioning that, after optimizing the process flow, the tube-and-rod stacking method has replaced the original quartz tube-fixed stacked preform with an OVD tube outer deposition fixed stacked preform. The multi-core optical fibers prepared by this method have greatly improved core eccentricity and precision in end-face arrangement, and they approach the geometric accuracy level of multi-core optical fibers prepared by the tube-and-rod drilling method. Different application requirements have different key indicators, thus requiring different multi-core fiber preparation technologies. For communication purposes, multi-core optical fibers with low attenuation, high core count, and low crosstalk are required. Therefore, the tube-and-rod stacking method is currently the applicable solution. In contrast, for device applications that require high geometric precision, the tube-and-rod drilling method is the suitable preparation method.

In addition, in recent years, the concept and technology of 3D printing have emerged, causing a wave of change in academia and industry, completely revolutionizing various industries and manufacturing. Applying 3D printing technology to fiber manufacturing is considered a milestone in the history of fiber manufacturing. However, the purity of printing quartz material is currently difficult to guarantee, making it unsuitable for the preparation of high-purity core rods. Therefore, the direction of developing multi-core optical fibers is to use 3D printing technology to print suitable adapter sleeves and combine them with conventional fiber preform preparation methods. With the continuous improvement and updating of 3D materials, as well as the maturation and development of 3D processing technology, multi-core optical fibers produced using 3D printing technology will gradually become practical and realize the diversification and multi-functionality of multi-core optical fibers in terms of materials, structures, and applications.

Against the backdrop of rapid development in information technology such as digital economy, smart cities, and big data processing, multi-core optical fibers have shattered the conventional capacity record of communication transmission systems, thanks to their advantage in spatial division multiplexing. Moreover, their inherent sensitivity, including bend sensitivity, temperature self−compensation, and multi−channel capabilities, has enabled their application in various fields such as communication, sensing, and lasers. As the fabrication technology of multi-core optical fibers matures, their advantages in medical endoscopy, probes, aerospace, and safety monitoring in transportation infrastructure are beginning to emerge.

5. Conclusions

multi-core optical fibers present a new opportunity for the development of communication technology and specialized sensing techniques. In comparison to traditional single-core fibers, multi-core optical fibers demonstrate advantages in terms of performance and diversified functionalities in communication and sensing applications. Although the economic advantages are not currently prominent, it is believed that the widespread application of multi-core optical fibers in high-bandwidth communication, sensing networks, and other fields could increase the market demand. If the market scale is sufficiently large, expanding production scale could potentially lower the unit costs, enhancing economic viability. The fabrication technology for multi-core optical fibers is becoming increasingly mature, and standardization and economies of scale are crucial factors for reducing economic costs. Standardizing multi-core optical fibers and their manufacturing processes contributes to improved production efficiency, and economies of scale may lead to cost reductions. These factors contribute to the rapid practicalization and commercialization of multi-core optical fibers.

Currently, researchers can customize designs and manufacture different multi-core optical fibers to meet the requirements of some certain specific systems. Additionally, the interconnection of multi-core optical fibers is a key factor in enhancing their position in various application domains. There are several techniques available to achieve the connection between single-mode and multi-core optical fibers (such as fan-in/fan-out devices) [47], including fusion splicing, fiber bundle methods, free-space optics, and three-dimensional integrated waveguide methods, can achieve the connection between single-core and multi-core optical fibers. Furthermore, the connection between multi-core optical fibers requires high−precision alignment of multiple fiber cores, making the fusion splicing scheme and algorithm complex.

In summary, through a survey of typical applications and the current status of fabrication technology for multi-core optical fibers, several directions for future efforts can be anticipated:

(1) High channel density and high−capacity transmission: In the future, multi-core optical fibers will develop towards higher channel density and larger transmission capacity. By increasing the number of fiber cores and optimizing the fiber structure, more channels can be integrated, and higher data transmission rates can be achieved. This will meet the growing demand for data communication and large−capacity transmission;

(2) Low insertion loss and low cross-coupling: multi-core optical fibers suffer from insertion loss and cross-coupling issues in optical signal transmission. Future developments will focus on reducing insertion loss and lowering cross-coupling to improve the transmission efficiency and reliability of optical signals. By optimizing the fiber structure, improving fabrication processes, and introducing new materials, lower insertion loss and better optical signal isolation performance can be achieved;

(3) Flexible layout and compatibility: The development of multi-core optical fibers will consider their flexible layout and compatibility with existing fiber optic systems. Future multi-core fiber designs will be more flexible to adapt to different wiring requirements and application scenarios. At the same time, to be compatible with existing single-core fiber optic systems, the interfaces and connection technologies of multi-core optical fibers will also be further improved;

(4) Integrated sensing and multifunctionality: multi-core optical fibers have extensive potential applications in the sensing and laser fields. Future developments will pay more attention to the application of multi-core optical fibers in sensing, such as temperature sensing, pressure sensing, strain sensing, 3D shape sensing, etc. By introducing sensing elements and photonic integrated devices into multi-core optical fibers, the integration and multifunctionality of fiber sensing can be achieved;

(5) Fabrication technology and material innovation: Future developments of multi-core optical fibers will continue to drive innovations in fabrication technology and materials. In terms of fabrication technology, efforts will be made to improve the fabrication process of multi-core optical fibers, enhance fabrication efficiency and accuracy. In terms of materials, new materials with better transmission properties and special functional materials that adapt to specific application needs will be explored.

Through advancements in these areas, future multi-core optical fibers will be able to meet higher communication demands, broader sensing applications, and more diverse optical requirements, thereby promoting the further development and innovation of fiber optic technology.

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