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Three-dimensional integrated optical fiber devices: emergence and applications

Tingting Yuan¹, Xiaotong Zhang², Shitai Yang³, Donghui Wang³ and Libo Yuan^{3*}

Abstract: This paper focuses on the utilization of quartz optical fibers as a foundational material for the miniaturization and integration of various optical paths and components into a single fiber, aiming to construct functional three-dimensional optical devices. It outlines the fundamental concepts and methodologies involved in creating such fiber-based integrated systems. Key technologies and implementation strategies for realizing three-dimensional optical devices are systematically reviewed. Furthermore, the paper elaborates on approaches to enhance the functionality of these fiber devices through laser microprocessing and material integration techniques. These advancements offer compact and integrated solutions for applications in optical fiber communication and sensing. Finally, from the perspective of facilitating scientific experiments on the light-matter interaction, the infinite possibilities of constructing "lab on/in optical fiber" were prospected. From the perspective of health and medical application demands, the clinical value and development potential of the new multifunctional optical fiber in the field of minimally invasive interventional surgery were explored.

Keywords: optical fiber; device; three-dimensional integration; component; fiber sensor

Introduction

In recent years, integrated optical technology has played an increasingly significant role in the fields of micro-nano optics and photonics. The concept of integrated optics was first introduced in 1969 by Dr. Miller S. E. of Bell Labs, with the aim of miniaturizing and integrating optical paths and optical signal processing systems—originally based on macroscopic optical experimental platforms—onto flat substrates for practical applications. Following this proposal, research on integrated optical systems utilizing dielectric materials as substrates was initiated. In 1972, Somekh and Yariv further advanced the field by proposing the integration of optical and electronic devices on the same semiconductor substrate¹. Since then, researchers have explored various materials and fabrication techniques to develop integrated optical devices and optoelectronic hybrid systems. Currently, planar photonic integration technology has become a key enabler for the development of the global photonics industry. Although planar substrate-based devices have remained dominant in optical communication systems, particularly with the rapid advancement of silicon-based photonic integration technology² in recent years,

which benefits from its compatibility with complementary metal oxide semiconductor (CMOS) processes, and it has increasingly become a mainstream direction in optoelectronic integration.

However, the question remains: how can three-dimensional photonic integrated devices and systems be constructed? Is it feasible to develop three-dimensional integrated optical systems by leveraging the two-dimensional structures of optical fibers? In addition to the well-established two-dimensional approach for large-scale photonic integration based on mature semiconductor technologies³, researchers have also explored three-dimensional integration of optical components on optical fibers using various fiber processing techniques and methodologies⁴.

No single technology can satisfy all the requirements of modern photonic systems. Although two-dimensional integration effectively addresses the challenges of high-density device integration and large-scale industrial batch production, fiber waveguide devices demonstrate distinct advantages in certain specialized functions⁵. For instance, in applications requiring flexible optical signal interconnection between two-dimensional system-on-chip architectures and

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distributed sensing of massive data, fiber-based devices outperform planar substrate devices⁶. In some specific scenarios, fiber waveguide devices play an irreplaceable role. Therefore, fiber-optic integrated photonic devices are expected to occupy an essential position in next-generation optical information systems and networks⁷. Meanwhile, the rapid development of smart cities, 5G technology, the internet of things (IoT), and cloud computing, along with emerging trends in 6G technology and the metaverse, has led to a dramatic increase in demand for information acquisition, processing, exchange, and transmission. Notably, data center communication and short-distance information transfer have experienced exponential growth⁸. Meeting the diverse demands for information interaction, transmission, and sensing presents new challenges for the advancement of next-generation fiber-optic photonic integrated devices.

For this purpose, this paper summarizes the method of integrating three-dimensional photonic devices on optical fibers based on refractive index guided special microstructure waveguide fibers. The core concept is to use optical fibers as cylindrical substrate materials to construct a three-dimensional integrated optical device system, miniaturizing complex optical paths and various optical components within a single optical fiber. The objective is to miniaturize traditional optical components and assemblies and "integrate" these components or systems into a single optical fiber based on new physical perspectives, in order to form optical fiber integrated photonics devices with multiple functions. This integration technology provides an innovative approach and solution for the three-dimensional integration of micro-optical devices, enabling the acquisition of fiber-integrated miniaturized fiber devices with different functions and integration degrees. Thus, it serves as a valuable technical foundation for meeting the integration and miniaturization requirements of photonic information processing systems.

The concept and development history of three-dimensional integration of optical fiber devices and components

The concept of constructing three-dimensional optical devices or components directly on optical fibers has a long-standing history. As early as 1978, K. Hill introduced the idea of fiber Bragg gratings and, for the first time, inscribed mirrors or filters into optical fibers⁹, thereby pioneering the integration of optical passive devices into optical fibers in three-dimensional space. In fact, extensive efforts have been made to investigate the feasibility of utilizing optical fibers as substrate materials for miniaturizing and integrating multiple optical devices and optical pathways within a single fiber. To this end, researchers have attempted to miniaturize and integrate optical components with varying functions and levels of complexity within the three-dimensional structure of quartz optical fibers. By leveraging the

versatile combination techniques of quartz optical fiber preforms and fiber-drawing technologies, various methodologies have been developed for achieving three-dimensional integration of complex optical circuits and devices within optical fibers. Through this innovative integration approach, multiple single-function optical devices can be compactly integrated within a single fiber, and individual functional units can be further combined to construct more sophisticated components. Consequently, by interfacing with external standard optical fibers, these miniaturized and integrated optical components can be seamlessly incorporated into a cohesive functional system, thereby significantly enhancing the overall performance of micro-fiber-integrated optical devices.

Unlike long-distance optical fiber communication, three-dimensional integrated optical devices based on optical fibers typically do not emphasize long-distance signal transmission. Instead, they primarily focus on the interaction between the short-distance waveguide embedded within the fiber and adjacent external waveguides, as well as the interaction between the internal waveguide and surrounding external media. These interactions are generally attributed to the coupling of the optical field at the fiber's end face or side surface with external materials^{10,11}. In certain specific scenarios, fiber-integrated optics also considers long-distance transmission properties and their interactions with the surrounding environment. For example, applications such as space division multiplexing in multi-core fiber-based optical communication systems^{12,13} and remotely deployed multi-optical-path distributed interferometry techniques^{14,15} represent such exceptional cases.

Ideal quasi-one-dimensional structural optical fiber: rotationally symmetrical and approximately infinite in length

As low-loss transmission waveguides for optical signals, optical fibers were originally designed as slender concentric cylinders exhibiting rotational symmetry. Initially developed as multimode fibers, they were subsequently optimized into single-mode fibers, with the zero-dispersion window shifted to the low-loss 1.55 μm wavelength band. These fibers are capable of transmitting signals over tens of kilometers with minimal loss, thereby approximating an ideal quasi-one-dimensional structure of effectively infinite length, as illustrated in Fig. 1. With advancements in optical fiber technology, while addressing the challenge of signal interference resistance during transmission, researchers discovered that such interference could be harnessed as sensing signals, leading to the emergence of a new application area: optical fiber sensing technology. In parallel, to achieve non-relay amplification in optical communications, fiber amplifiers and fiber lasers were developed. These innovations not only resolved the

technical limitations of long-distance optical transmission but also provided a foundation for the rapid growth of high-power industrial processing. Furthermore, the demand for mitigating nonlinear effects during high-power, long-distance transmission has driven the development of novel fiber technologies, such as photonic crystal fibers and hollow-core fibers. In summary, driven by the demands of the optical fiber communication industry and the pursuit of multifunctional capabilities, the near-ideal one-dimensional structure of optical fibers has gradually been modified and diversified.

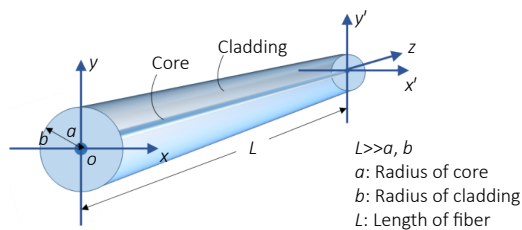


Fig. 1 | Optical fiber can be regarded as quasi-one-dimensional structures, characterized by perfect rotational symmetry and an approximately ideal infinite length.

Breaking the perfect symmetry: expanding from a one-dimensional to a two-dimensional structure

The transition from one-dimensional to two-dimensional cross-sectional structures disrupts the simplicity and perfect rotational symmetry inherent in one-dimensional configurations, thereby introducing diverse opportunities for functional advancements in optical fibers, as illustrated in Fig. 2. For example, multi-core optical fibers incorporate multiple waveguide paths arranged in parallel within a single fiber¹⁶, as depicted in Fig. 2(a). These multi-core fibers represent a key approach for enhancing the capacity of optical communication systems within a two-dimensional framework. Additionally, core-hole hybrid integrated fibers enable the introduction of microfluidic liquids or gases into the fiber structure, resulting in what are known as microfluidic optical fibers^{17–19}, as shown in Fig. 2(b). Such fibers offer an ideal platform for extended light-matter interactions, facilitating the sensing of liquid and gaseous media.

When the microstructure of the fiber features an arrangement of micropores that satisfies the conditions of a photonic bandgap, a novel type of photonic crystal fiber can be realized^{20–22}, as demonstrated in Fig. 2(c). These fibers provide an effective solution for minimizing nonlinear effects during the transmission of high-energy laser beams through air, while also enabling new approaches for generating ultra-broadband light sources. With growing understanding of the anti-resonance guiding mechanism, hollow-core optical fibers have recently emerged as a promising addition to the family of optical fibers^{23,24}, as illustrated in Fig. 2(d).

These fibers offer advantages such as ultra-wide bandwidth and exceptionally low nonlinearity, highlighting their significant potential for future optical communication systems, particularly in short-distance, high-speed data transmission applications, such as those found in data centers.

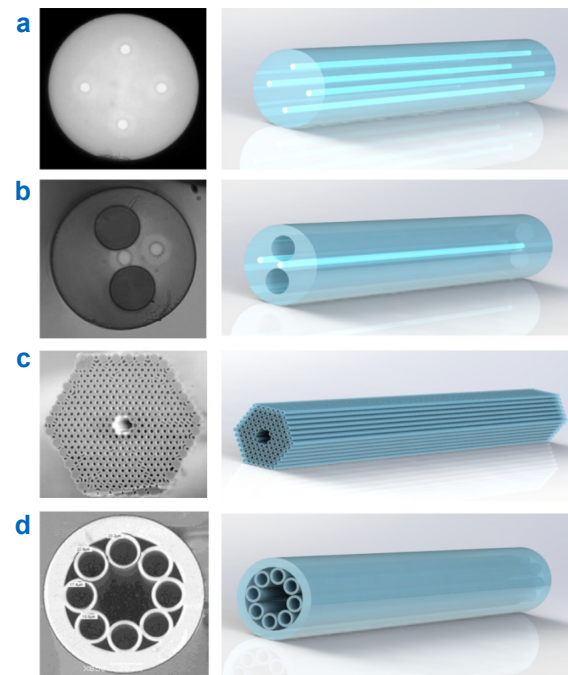


Fig. 2 | Breaking rotational symmetry: from simple rotational symmetry structures to complex two-dimensional cross-sectional structures. (a) Four-core optical fiber. (b) Core-hole hybrid integrated microfluidic optical fiber. (c) Hollow-core photonic crystal fiber. (d) Anti-resonant hollow-core optical fiber simplified to a circle of microtubes. Figure reproduced from: (c) ref.²², AAAS; (d) ref.²³, Optical Society of America.

Breaking the ideal of near-infinite length: variations in the third dimension have opened up the path for the integration of three-dimensional optical fiber devices

The development of three-dimensional optical fiber devices begins with a fundamental periodic variation in the refractive index, known as a "fiber grating", which is fabricated on the uniform core of an optical fiber²⁵, as illustrated in Fig. 3. This seemingly simple innovation enables the integration of three-dimensional optical components, such as "wavelength-selective reflectors" or "wavelength-selective filters", directly into the optical fiber. This represents a pioneering advancement that sets the direction for the integration of three-dimensional optical fiber devices.

Building upon modifications in the two-dimensional cross-section, researchers have begun to explore the construction of fully three-dimensional optical fiber devices and components. A representative example is the three-dimensional shape sensor based on four-core optical fibers,

as shown in Fig. 4(a), which exemplifies the capabilities of integrated three-dimensional optical fiber systems. This sensor utilizes backscattered signals generated by localized strain to detect information regarding bending and torsion, which is then processed to reconstruct the spatial deformation of the fiber. It is capable of continuously tracking the real-time shape and position of dynamically moving objects with unknown trajectories²⁶. By integrating multiple fiber Bragg grating (FBG) devices along a multi-core fiber and arranging multiple FBG arrays, the spatial distribution of the four cores within the same fiber can be leveraged to construct a large-scale, micro-integrated optical system. As a result, differences in FBG responses at various spatial locations enable the reconstruction of the three-dimensional shape of the multi-core optical fiber.

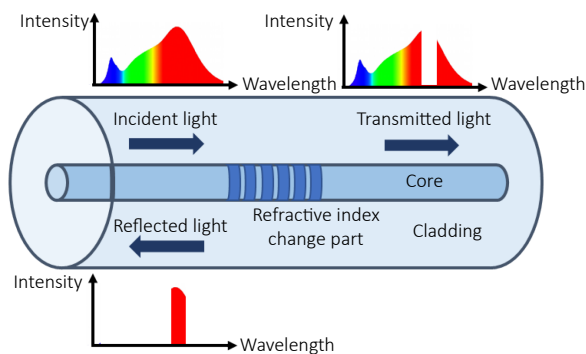


Fig. 3 | Breaking the ideal of infinite length: the three-dimensional variation, starting with a simple periodic refractive index change and formed fiber Bragg grating.

In 2012, Moore et al.²⁷ proposed a method for analyzing distributed fiber bending sensing measurement data to address the challenge of reconstructing spatial three-dimensional shapes using multi-core fiber gratings. The authors modeled the bending sensing optical fiber as a Kirchhoff elastic rod. Consequently, based on Kirchhoff elastic rod theory, the spatial bending characteristics of the sensing

optical fiber can be described using the Frenet-Serret equation, which consists of a set of differential equations representing three-dimensional spatial bending. Solving this equation enables the determination of the specific displacement and orientation of the optical fiber strain. As illustrated in Fig. 4(b), a four-core optical fiber primarily comprises a central core located at the center of the cladding and three peripheral cores arranged in an equilateral triangular configuration. The four-core fiber Bragg grating (FBG) bending sensor depicted in Fig. 4(b) is formed by inscribing a Bragg grating array onto the four-core fiber, typically fabricated using the phase mask method. In practical grating bending sensing systems, local morphological changes in the optical fiber can be derived from its local bending radius and direction. These morphological data allow for the reconstruction of the overall three-dimensional deformation of the optical fiber. Therefore, by arranging multiple FBG sensing arrays along the length of the fiber, it is possible to reconstruct the three-dimensional morphological variations of the entire optical fiber. In each measurement section of a multi-core optical fiber, the three-dimensional curvature at that location is determined by simultaneously measuring the strain across multiple cores. Subsequently, interpolation or curve fitting techniques are applied to obtain a continuous curvature function along the entire length of the optical fiber. Finally, three-dimensional shape reconstruction is achieved through the application of a dedicated reconstruction algorithm.

We can see that, based on the idea of changing the geometric structure or refractive index distribution along the longitudinal—the third dimension of the optical fiber, a new branch of research on the three-dimensional integration of optical fiber devices and components has been initiated. Combined with the enrichment and evolution of microstructure fibers (the two-dimensional geometric structure of the cross-section), the three-dimensional integration technology of fiber optic devices has made considerable progress and development in application fields such as fiber lasers and fiber optic sensors.

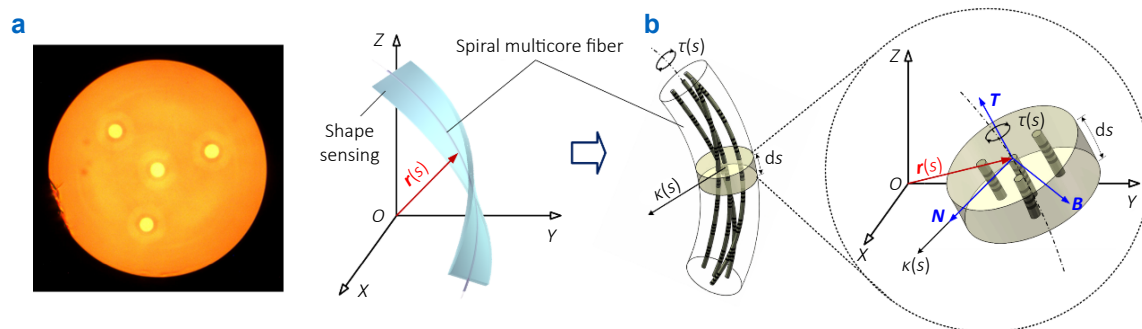


Fig. 4 | Illustrates a typical three-dimensional optical fiber device capable of perceiving shape variations in three-dimensional space. (a) Four fiber cores are arranged on the two-dimensional cross-section of the optical fiber, forming a triangular configuration. (b) Along the third dimension, four arrayed fiber Bragg gratings are inscribed. By measuring the strain variations across different fiber gratings, the three-dimensional spatial shape of the fiber can be reconstructed.

Functional expansion through two-dimensional integration of optical fiber devices and components: structural modifications to fulfill functional requirements

In order to enhance the density of optical communication transmission channels, the concept of multi-core fibers, which integrate multiple optical information channels within a single optical fiber, was introduced in 1979^{16,17}. During the early stages of practical application of multi-core fiber technology in optical communications, two major challenges were identified: first, the interconnection and splicing of multi-core fibers posed significant technical difficulties; second, there was substantial long-range cross-talk between the individual fiber cores. As Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) technologies have advanced and matured, the advantages of multi-core fibers in addressing high-density channel communication have gradually diminished. However, with the growing demand for increased channel capacity, multi-core fiber technology based on space division multiplexing has regained attention. Over the past decade, significant progress has been made in inter-core isolation techniques^{28,29} and multi-core fiber splitting and connection technologies^{30–32}. The development of innovative multi-core fiber manufacturing methods not only revitalizes multi-core fiber communication but also positions it as a key solution for future optical communication capacity expansion. Furthermore, these advancements demonstrate promising potential for enabling large-scale distributed sensing of environmental information over

long distances. This progress also contributes to the integrated development of communication and sensing systems.

Figure 5 illustrates several commonly used multi-core optical fiber configurations. Specifically, Fig. 5(a–f) depict multi-core fibers with up to seven cores, all with a core diameter of 125 μm and no isolation trench surrounding the cores. These structures are suitable for short-distance transmission and can serve as the foundation for constructing three-dimensional optical fiber devices or components, as well as short-distance optical fiber sensors. Figures 5(g–i), on the other hand, represent multi-core fibers with isolation trenches around each core^{33,34}. These fibers have outer diameters of 225 μm and 250 μm , respectively, and are capable of supporting weakly coupled single-mode long-distance optical communication.

To better utilize the diverse functionalities of three-dimensional devices, researchers have designed and developed various multi-waveguide fibers featuring distinct transverse two-dimensional structures, as illustrated in Fig. 6. When building the integrated optical devices and microsystems directly on optical fibers, remote transmission is not required; therefore, each core does not incorporate a low-refractive-index isolation layer. This structural design aims to facilitate key tasks such as optical wave control, optical wave signal exchanging, signal amplification, fiber-based information processing, and information extraction of the interaction between optical fibers and the surrounding environment in the development of integrated optical paths and devices.

Figure 7 illustrates several core-hole integrated optical fibers that we have developed and fabricated in recent years.

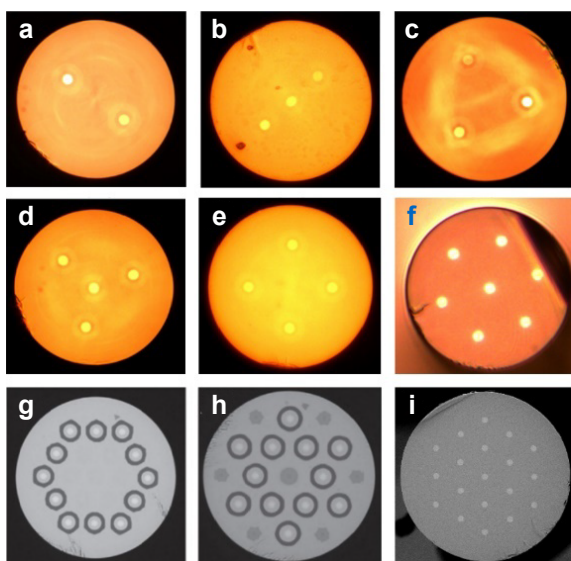


Fig. 5 | Several typical multi-core optical fibers. (a–f) Multi-core optical fibers are used for short-range sensing applications. (g–i) Multi-core optical fibers are used for long-distance communication. Figure reproduced from: (g) ref.³³, (h) ref.³⁴, Optical Society of America.

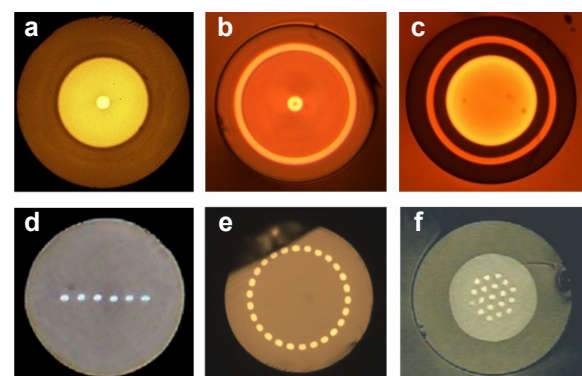


Fig. 6 | Special multi-core optical fibers for device construction. (a) Double-clad optical fibers. (b) Coaxial dual-waveguide optical fiber. (c) Large-core-diameter coaxial dual-waveguide optical fiber. (d) Six-core array core optical fiber. (e) Annular multi-core optical fiber. (f) 19-core multi-core double-clad optical fiber.

These optical fibers combine both optical waveguiding capabilities and microfluidic functionalities. Specifically, they feature a dual-function structure: one for guiding light waves and another for enabling microfluidic transport—such as the extraction of body fluids or the delivery of medicinal solutions. Additionally, the micro-holes embedded in the fiber can be used to introduce electrode materials—for instance, by embedding solid electrodes at both ends and filling the central region with liquid metal to establish an internal current transmission channel. This hybrid integration significantly enhances the interaction between light and the introduced substances. Furthermore, it facilitates long-range interactions between the guided light field and external micro- or nanoscale substances, offering a promising platform for integrating novel functional devices directly onto the optical fiber. Such integration is particularly beneficial for incorporating active control and microsensing components into optical fibers. This unique fiber structure, which integrates optical waveguides and microfluidic channels within a single fiber, holds great promise for the advancement of fiber-based microfluidic sensing technologies. Microstructured optical fibers with micrometer-scale pores can accommodate trace volumes of gases or liquids (in the range of microliters to nanoliters), making them ideal candidates for trace-level detection and analysis. The one-dimensional channel structure provides an optimal environment for extended interaction between the sample and the guided light, thereby overcoming the limitations of conventional optical fibers. This innovation offers irreplaceable advantages in various application domains, including biochemical analysis, interventional sensing, and therapeutic monitoring.

To enhance the interaction between the evanescent field and the microfluidic material, a core with a higher refractive index is suspended on the inner wall of the quartz capillary, forming what is known as a suspended core fiber, as illustrated in Fig. 7(a)³⁵. This configuration allows the microfluidic material introduced into the central air hole to directly interact with the evanescent optical field within the optical waveguide. The ring-shaped core capillary fiber can be conceptualized as a fiber structure created by introducing a central air hole within the core of a multimode optical fiber and retaining a circular ring of high refractive index material to serve as the waveguide, as shown in Fig. 7(b). This effectively enables the microfluidic material to be introduced at the center of the ring-shaped optical waveguide, thereby facilitating its interaction with the propagating light waves. In the case of the double-hole single-mode optical fiber depicted in Fig. 7(c), the two side air holes can not only accommodate microfluidic materials but also support microfluidic functionalities. Additionally, metal electrodes can be inserted into these air holes to realize an electro-optic modulator integrated within the optical fiber structure.

To enable the integration of microfluidic substances into

optical fibers while simultaneously establishing a dual-channel interferometer configuration, various dual-core optical fibers incorporating microporous structures have been developed, as illustrated in Fig. 7(d–f). Figure 7(d) depicts a dual-core optical fiber consisting of a central core and an eccentric core. Two air holes, each with a diameter of approximately 40 μm , are symmetrically positioned on either side of the central core¹⁸. This fiber design is applicable not only in microsensing-integrated devices but also in the realization of interferometric electro-optic modulators. The air holes can accommodate embedded electrodes, and the dual-core architecture supports the construction of Michelson or Mach–Zehnder interferometers. Similarly, as shown in Fig. 7(e), a dual-core fiber comprises a central core and an eccentric core, with an air hole located at a position symmetrically opposite to the eccentric core^{30,36}. This fiber structure is particularly suitable for the development of fiber-based microfluidic sensing systems. The eccentric air holes allow for interaction between the evanescent light field and the microfluidic medium, while the reference beam travels through the central core, remaining spatially separated from the sensing region. Such fibers can be employed in the development of in-fiber optical microfluidic devices for applications including refractive index measurement, chemiluminescence and fluorescence detection, and electrophoretic separation with integrated sensing. In certain cases, to enhance the interaction between the evanescent field and the microfluidic substances, dual-core optical fibers have been designed with exposed fiber cores suspended on the inner wall of a capillary, as illustrated in Fig. 7(f). In addition to a fiber core suspended on the inner capillary wall, a second fiber core is introduced at the center of the capillary wall to form the interferometer structure. This configuration enables the realization of an ideal microchemical reactor for interferometric monitoring of photochemical reactions within capillaries¹⁹. Figures 7(g–i) present several multi-core fiber designs featuring a central air hole, characterized by a large central air channel and multiple elliptical, high-refractive-index waveguide cores embedded along the inner wall of the central air hole. These multi-core fibers have been utilized in inner-wall fiber grating systems for microfluidic monitoring³⁷ and other related applications.

Photonic crystal fibers (PCFs) are widely applicable in biochemical sensing, strain and temperature measurement, and various optical integrated devices due to their precisely arranged microstructured porous geometry. Solid-core photonic crystal fibers allow for the infiltration of liquids or polymers into the surrounding microholes, enabling the detection of chemical substances or biomolecules through evanescent wave sensing, as illustrated in Fig. 8(a, b)^{38,39}. This configuration facilitates the interaction between light and the infiltrated materials, thereby supporting the measurement of gas concentrations or the detection of biomolecules. Another variant of photonic crystal fibers is the photonic bandgap fiber, in which a hollow core replaces the solid center. The photonic bandgap effect confines light within the central air hole. When this hollow core is filled

with transparent materials, the optical path can simultaneously function as a medium for material interaction, modulating the light field accordingly, as shown in Fig. 8(c, d)^{40,41}. The injection of different materials into the core alters the refractive index contrast between the core and cladding, thereby modifying the transverse mode profile. These unique properties make PCFs highly compatible with opto-electronic devices, biochemical sensors, and molecular detection systems.

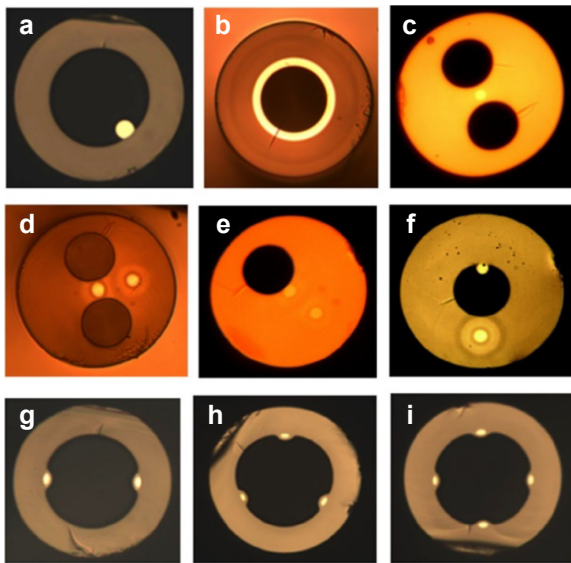


Fig. 7 | Cross sections of several typical core-hole combination special fibers. (a) Hollow suspended-core fiber. (b) Hollow ring-core fiber. (c) Dual-hole single-core fiber. (d) Dual-hole asymmetric double-core fiber. (e) Single-hole asymmetric double-core fiber. (f) Suspended-core and offset-core combination fiber. (g-i) Hollow fused-embedded multi-elliptical-core fiber. Figure reproduced with permission from ref.³⁵, CLP.

Traditional solid-core optical fibers are inherently limited by material properties, such as nonlinearity, dispersion, Rayleigh scattering, and susceptibility to optical damage. Microstructure hollow-core optical fibers offer a promising solution to these fundamental limitations, providing an ideal and versatile medium for applications including high-power lasers, nonlinear optics, biophotonics, quantum optics, fiber sensing, and optical communications. In recent years, the rapidly advancing anti-resonant

hollow-core fiber technology has demonstrated advantages such as broadband optical transmission and a high laser damage threshold. Several representative anti-resonant hollow fiber structures that have emerged in recent years are illustrated in Fig. 9^{24,42–46}.

Current research on the two-dimensional integration of optical fiber devices and components is characterized by rapid progress in both structural design and multifunctional integration. Multi-core fibers originally limited by splicing challenges and inter-core crosstalk, have regained importance through space division multiplexing and advances in isolation techniques and connection technologies, positioning them as a key strategy for high-capacity communications. Beyond communications, multi-core fibers with diverse two-dimensional layouts are being adapted for short-distance sensors, integrated devices, and large-scale distributed sensing, highlighting their versatility. Parallel to this, micro-structured and core-hole fibers have emerged as hybrid platforms combining light guidance with microfluidic transport, electrode integration, and electro-optic modulation, enabling applications such as biochemical sensing, therapeutic monitoring, and optofluidic reactors. PCFs expand these capabilities further by offering precisely engineered porous geometries that enhance evanescent-field interactions, with solid-core PCFs facilitating biochemical detection and hollow-core bandgap PCFs enabling tunable light-matter interactions. Recently, anti-resonant hollow-core fibers have shown breakthroughs in broadband transmission, laser damage resistance, and nonlinear optical applications, overcoming the intrinsic material limits of traditional solid-core fibers. Overall, research is trending toward highly integrated fiber platforms that merge communication, sensing, and active control functions, establishing optical fibers as multifunctional microsystems for next-generation photonics.

Technical approaches for the three-dimensional integration of optical fiber devices and components: methods and technologies for the third dimensional transformation

To realize devices with different functions, it can be achieved by making changes to the third dimension of the

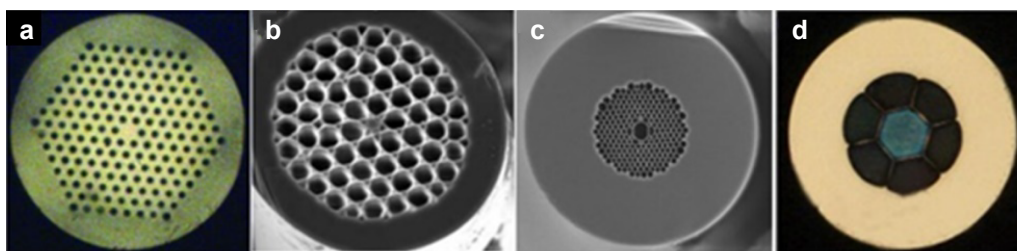


Fig. 8 | Cross-sectional views of several typical photonic crystal fibers. Figure reproduced from: (a) ref.³⁸, (c) ref.⁴⁰, (d) ref.⁴¹, Optical Society of America; (b) ref.³⁹, Springer Nature.

optical fiber. The primary technical approaches are outlined as follows.

The third dimensional geometric structure mutation: side polishing, end-face polishing, and splicing of heterogeneous optical fibers

Grind one side of the optical fiber into a D-shaped profile to facilitate the fabrication of three-dimensional devices

The optical fiber can be processed into a D-shaped configuration through the side grinding preparation method^{11,47}. Owing to its controllable polishing area length and surface roughness, this type of optical fiber has emerged as a multi-functional platform that facilitates the interaction between multiple materials and evanescent fields⁴⁸. It is widely utilized as a substrate for various photonic devices, including couplers⁴⁹, filters⁵⁰, polarizers⁵¹, modulators⁵², and sensors⁵³.

Several representative applications of D-shaped optical fibers are illustrated in Fig. 10. These fibers are employed in evanescent field sensors to enable biological and chemical sensing based on refractive index changes. This constitutes the earliest and most prevalent application of D-shaped optical fibers, as depicted in Fig. 10(a). In 2011, researchers leveraged the discovery that the linear dispersion characteristics of Dirac electrons in graphene exhibit a strong S-polarization effect within the communication band, enabling the propagation of transverse electric mode surface waves. Based on this principle, a graphene-coated D-shaped optical fiber was developed to realize a broadband fiber polarizer with an extinction ratio of 27 dB, as shown in Fig. 10(b)⁵⁴. In 2024, a broadband ultra-sensitive all-fiber photodetector was fabricated on a D-shaped optical fiber platform. Utilizing rGO:ZnO nanostructured materials integrated with intercalated finger electrodes, an in-situ monitoring structure for optical signal intensity was developed, forming a fully integrated all-fiber photodetector, as illustrated in Fig. 10(c)⁵⁵.

Construct fiber end mirrors or lenses with three-dimensional structures through geometric polishing of the fiber end faces

Fiber end polishing technology offers a versatile and precise

method for beam control of light emitted from the fiber end. As illustrated in Fig. 11(a), by positioning the fiber end within a polishing device, various microstructures—such as inclined, wedge-shaped, and multi-faceted prism-like configurations—can be fabricated directly at the fiber tip. Additionally, axially symmetric lens structures, including conical and truncated conical shapes, can be produced. This technique can also be integrated with fiber end ball-fusing and end cap welding processes to construct composite fiber end lens structures, as demonstrated in Fig. 11(b). The fabrication of wedge-shaped lenses¹⁰ and multi-pyramidal lenses⁵⁶ at the fiber end enables the conversion of elliptical beams into Gaussian beams, thereby facilitating efficient beam coupling between semiconductor lasers and optical fibers. Similarly, conical fiber end structures support the generation of Bessel beams, offering beam compression and shaping capabilities that enhance coupling efficiency with on-chip waveguides.

Compared to conventional bulk lens assembly methods, fiber end lenses fabricated through integrated polishing techniques offer advantages in terms of structural simplicity, enhanced stability, and improved reliability. These fiber end modifications have diverse applications. As shown in Fig. 11(c), various surface plasmon resonance (SPR) sensing probes^{57,58} can be designed and fabricated for biochemical sensing purposes. A 45° reflective bevel or conical structure at the fiber end can enable optical path coupling between different cores in multi-core fibers, functioning as an ultra-compact passive device with significant applications in fiber optic sensing^{59,60}, as illustrated in Fig. 11(d). The 45° reflective surface can redirect the beam by 90°, allowing side-facing light output along the fiber axis. Such polished fiber end lenses are applicable in interventional optical coherence tomography (OCT) imaging⁶¹, as shown in Fig. 11(e).

Moreover, by polishing the ends of multi-core or ring-core fibers to form conical or prism-shaped structures, beams from the edge cores or ring cores can be reflected and focused across different planes. The resulting focused beams generate a deep optical potential well capable of trapping micro particles⁶². By integrating specialized optical fibers with microstructured lenses at the fiber ends, additional functionalities—such as particle ejection⁶³, transport⁶⁴, and analysis—can be achieved. These capabilities

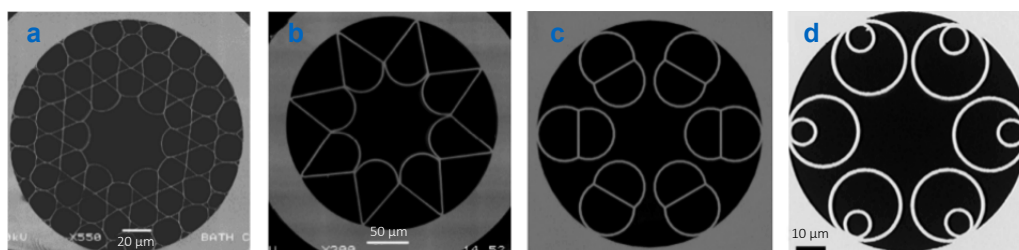


Fig. 9 | Cross-sectional structural diagrams of several representative anti-resonant hollow-core optical fibers. Figure reproduced from: (a) ref.⁴³, (b) ref.⁴⁴, Optical Society of America; (c) ref.⁴⁵, under a Creative Commons Attribution License; (d) ref.⁴⁶, IEEE.

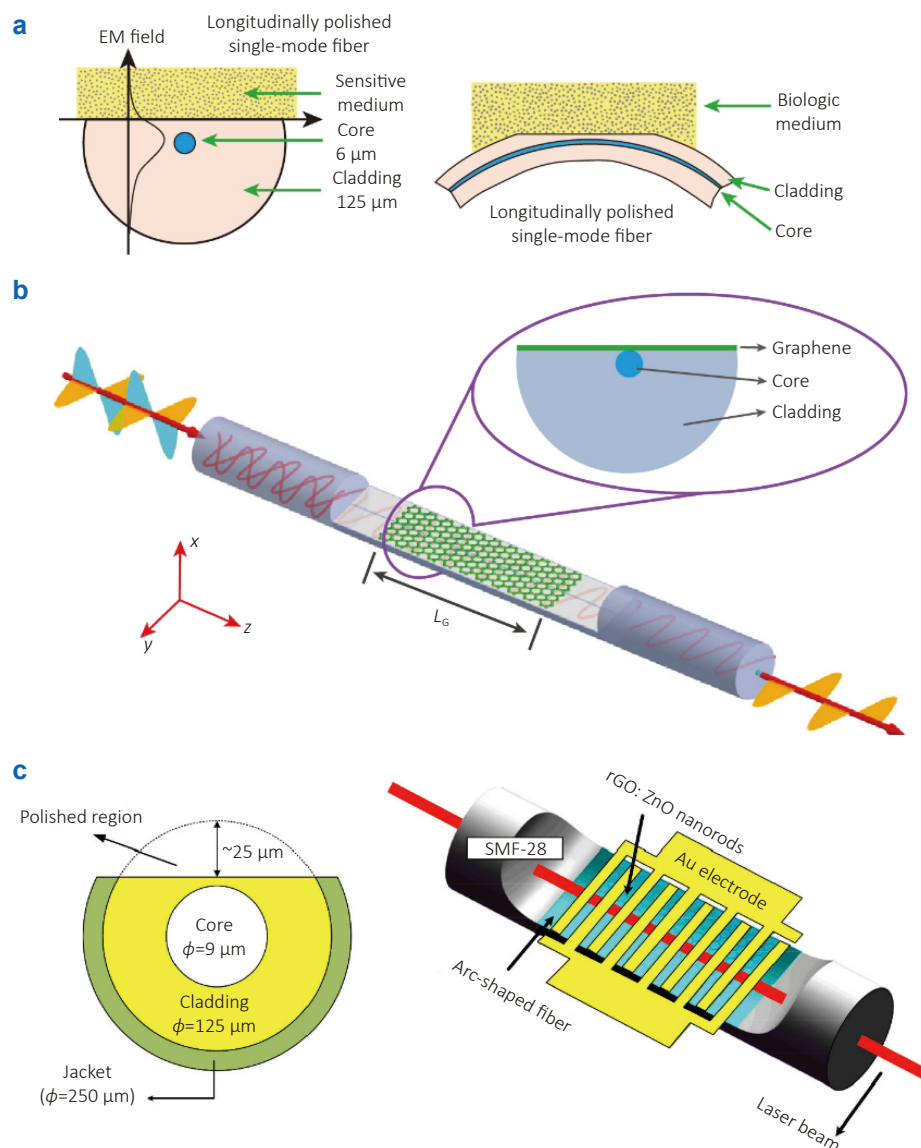


Fig. 10 | Several typical applications of D-shaped optical fibers. (a) Biological and chemical sensing. (b) Broadband polarizer. (c) Fiber optic in-situ photodetector. Figure reproduced from: (b) ref.⁵⁴, Springer Nature; (c) ref.⁵⁵, IOP Publishing.

hold great promise for applications in single-cell manipulation and biological analysis, as depicted in Fig. 11(f)⁶⁵.

Three-dimensional microstructural composite devices are fabricated through post-welding etching of heterogeneous optical fibers

Chemical etching is a widely adopted technique for three-dimensional microfabrication of optical fibers, enabling the transformation or reshaping of specific cross-sectional regions of an optical fiber into intricate three-dimensional microstructured optical devices. This microfabrication process relies on precise control of the etching rate. To implement this technique, phosphorus pentoxide (P_2O_5) is introduced into the silica glass during the standard optical fiber manufacturing process. When the doped fiber is exposed to hydrofluoric acid (HF), the etching rate of the

phosphorus-doped region is approximately 100 times faster than that of pure silica⁶⁶. Consequently, by designing and fabricating specialized doped optical fibers, and splicing them at the tips of standard single-mode fibers or between doped and standard fibers, followed by controlled etching, various novel photonic devices can be efficiently fabricated, as illustrated in Fig. 12.

The microdisk resonant cavity device shown in Fig. 12(a) is fabricated by splicing a short segment of P_2O_5 -doped optical fiber with a unique structure between two sections of coreless optical fiber. The microdisk itself is formed from a second coreless fiber segment approximately 16 μm in length. After the entire structure is immersed in a 40% hydrofluoric acid solution, etching is completed within 12 minutes. The thickness of the resulting micro-resonator disk can be adjusted by varying the length of the second

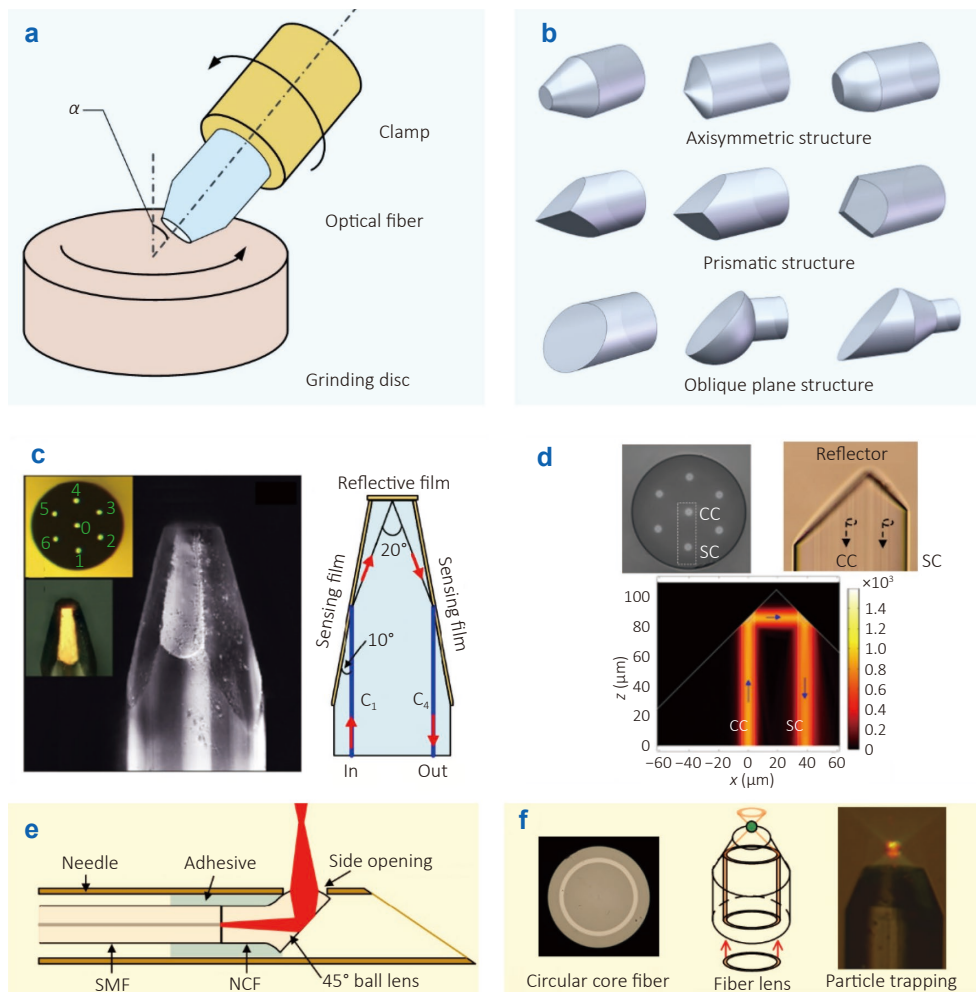


Fig. 11 | Micro-machining technology for fiber optic ends based on precision polishing and grinding. (a) Processing principle. (b) Examples of processable fiber end structures. (c) Fiber end polishing microstructure for surface plasmon resonance (SPR) sensing probes. (d) Fiber end polishing microstructure for multi-core optical fiber end reflection couplers. (e) Fiber end polishing microstructure for interventional OCT probes. (f) Fiber end polishing structure for beam focusing and optical manipulation applications. Figure reproduced with permission from ref.⁶⁵, IRLA.

coreless fiber segment⁶⁶.

Figure 12(b) presents a core microfilament support structure designed for in-situ sensing applications. The selection of the microfilament's diameter and refractive index profile is based on the requirement to optimize the interaction between the waveguide evanescent field and the surrounding medium under investigation. This structure is created by splicing two standard single-mode fibers with a specially designed doped fiber segment in between. To ensure mechanical stability of the microfilament, the doped fiber has been structurally optimized during design, allowing for successful etching of the final configuration⁶⁷. The gap between the exposed microfilament core and the adjacent supporting components prevents interference between the measurement field in the core region and the surrounding structural elements. The entire structure is composed of fused silica, thereby offering excellent mechanical, chemical, and thermal stability.

The three-dimensional geometric structure gradient: tapering and twisting

By applying localized heating and fused the optical fiber, its overall structure can be modified to construct the desired three-dimensional optical fiber devices. This section provides an overview of the preparation methods for fused fiber tapering and twisting devices.

Three-dimensional optical fiber tapering devices constructed by heating and drawing

There are typically several common types of optical fiber taper deformations, including unilateral taper shape deformation, bi-taper shape deformation, S-shaped taper deformation, and periodic taper deformation, as illustrated in Fig. 13. In the case of a tapered deformation structure, one end maintains the original optical fiber structure, while the diameter of the fiber gradually decreases uniformly along

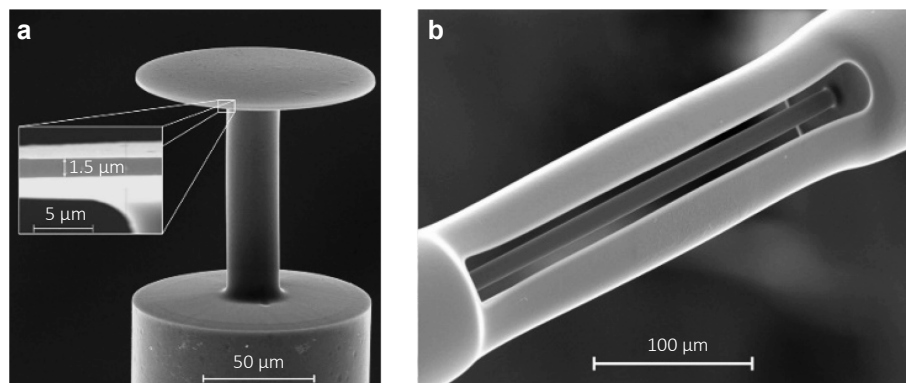


Fig. 12 | Illustrates the micro-processing of optical fibers into various shapes through chemical etching. (a) Microdisk resonant cavity devices fabricated at the fiber end. (b) Structural devices supported by microfilaments within the fiber core for field detection. Figure reproduced with permission from: (a) ref.⁶⁶, IEEE; (b)⁶⁷, Optical Society of America.

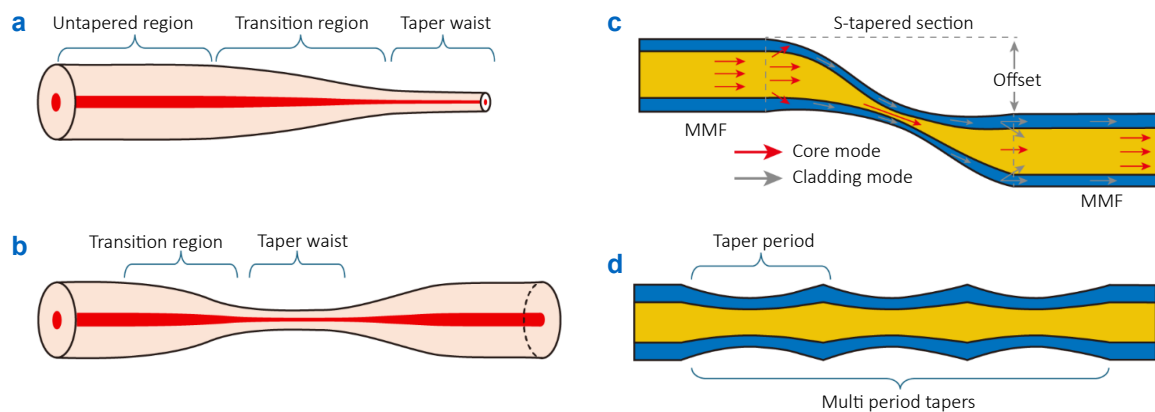


Fig. 13 | Several typical three-dimensional optical devices of fiber tapers and their combined structures. (a) Unilateral taper shape deformation, (b) bi-taper shape deformation, (c) S-shaped taper deformation, and (d) periodic taper deformation.

the axial direction at the other end, resulting in a conical configuration^{68,69}. For the bi-tapered deformation structure, both ends preserve the original fiber structure, and the fiber diameter uniformly reduces toward the center along the axial direction, forming a bi-tapered geometry^{70,71}. An S-shaped taper fiber is developed based on a bi-tapered structure, with the waist region exhibiting a curved S-shaped profile^{72–75}. Periodic taper deformation refers to a three-dimensional fiber structure formed by cascading multiple bi-tapered deformation units at regular intervals, which can be utilized to fabricate long-period fiber grating devices⁷⁶.

The core concept in fabricating three-dimensional optical fiber devices using tapered optical fibers lies in modulating the original transmitted light field. This modulation is achieved through structural deformation, which induces mode conversion and facilitates energy exchange among different modes of the propagating light field within the fiber. Such modulation manifests as variations in the light field, characterized by enhanced and diminished interference effects due to mode coupling. Consequently, the principle can be applied to develop various optical components,

including sensors, fiber Bragg grating reflectors, and optical filters.

Three-dimensional structured optical fiber devices fabricated through heating and twisting

Heating and twisting refers to a three-dimensional helical structure formed by locally heating an optical fiber and simultaneously applying torsional deformation, thereby enabling modulation of the light field propagating through the fiber. Based on the structural characteristics of the fiber core and its degree of off-axis displacement, helical optical fiber devices can be broadly classified into two main categories.

The first category can be further divided into two subtypes: 1) When the fiber core exhibits a non-circular cross-sectional geometry, a three-dimensional helical structure can be generated through thermal softening and torsional deformation, as illustrated in Fig. 14(a–d)⁷⁷. 2) When the core of a circular fiber is slightly offset from the center of the fiber end face, the off-axis displacement leads to a weak helical perturbation upon twisting, as shown in Fig. 14(e, f). This perturbation facilitates coupling

between the fundamental mode and higher-order modes, and such devices are commonly referred to as helical fiber gratings or chiral fiber gratings. These structures typically have a torsion period of approximately 500 μm and are widely applied in sensors⁷⁸, spectral filters⁷⁹, and vortex beam generators⁸⁰.

The second category involves fibers in which the core is inherently off-centered relative to the fiber end face. Upon torsional processing, the core forms a pronounced helical spring-like structure, as depicted in Fig. 14(g, h), guiding the propagating light waves along the helical path. This configuration exhibits a strong off-axis effect, resulting in significant optical loss. The device is typically short in length, with a torsion period exceeding 1 mm. Due to its ability to substantially alter the propagation direction of light, this type of device is commonly employed in SPR biosensors⁸¹, helical interferometers⁸², and similar applications.

The principle of the vortex beam generator fabricated using double-clad optical fibers is illustrated in Fig. 14(i, j). In this configuration, a Gaussian-distributed fundamental mode is converted into a ring-shaped vortex mode via a core micro-off-axis helical fiber grating. High-performance vortex mode generation typically necessitates spiral fiber gratings with characteristics such as minimal off-axis displacement, adequate sampling length, and high uniformity. Figures 14(k, l) depict the transmitted mode spectrum and interference spectrum of the helical long-period fiber grating. The device exhibits an insertion loss of less than 1 dB, with a mode coupling efficiency of up to 99.5% (-23.3 dB)⁸³. Furthermore, by employing chirped fiber gratings with arbitrarily variable periods, a flattened and broadened coupled spectrum can be achieved, thereby enhancing the operational bandwidth of the vortex generator⁸⁴.

The three-dimensional refractive index structure gradient: thermal diffusion control method

The waveguide structure along the core can be modified by adjusting the refractive index of the core. For example, ultraviolet excimer lasers can be employed to periodically modulate the refractive index of the fiber core, thereby forming fiber Bragg gratings. Similarly, femtosecond lasers can be utilized to alter the fiber core structure, enabling the fabrication of various specialized optical devices. This topic has already been discussed previously and will not be reiterated here.

This section introduces a method for fabricating three-dimensional optical fiber devices by gradually modifying the refractive index of the fiber core through thermal diffusion. When optical fibers are exposed to a high-temperature environment, dopants within the fiber migrate from regions of high concentration to regions of low concentration—a process known as thermal diffusion. By controlling the thermal diffusion process, the doping concentration distribution can be manipulated, allowing for the reconstruction of the three-dimensional refractive index profile

within the fiber while maintaining the original dimensions and shape of the cladding, as illustrated in Fig. 15⁸⁵. In 1991, Shigihara et al.⁸⁶ successfully fabricated a single-mode conical fiber-type mode field adapter using thermal diffusion technology, achieving low-loss coupling between different waveguide components. Since then, extensive theoretical and experimental studies have been conducted on thermal diffusion using various approaches, and the technique has been applied to the development of a wide range of optical devices.

Optical fiber thermal diffusion technology is gaining increasing prominence in the fabrication of a wide range of optical fiber devices. Currently, this technology has been successfully applied to optical isolators^{87,88}, optical fiber interferometers^{89,90}, adjustable optical attenuators⁹¹, pump power combiners^{92,93}, filters⁹⁴, optical fiber sensors^{95,96}, colorimeters⁹⁷, mode field adapters^{98,99}, and optical fiber couplers^{100,101}. The application scenarios of optical fiber thermal diffusion devices can generally be categorized into three primary functions: mode field expansion, mode field matching, and mode field collimation.

Reconfiguration of the three-dimensional structure: assembly of microdevices

Assembling optical fibers with diverse structural configurations using microstructured optical devices represents an effective approach for constructing three-dimensional integrated optical fiber microsystems. For instance, micro-units with resonant functionalities—such as microsphere resonators^{102–106} and microbubble resonators^{107–109}—can be integrated with fiber waveguides of varying structures to realize microsphere-based resonant lasers¹⁰² or sensing devices¹⁰⁹.

The integration of hollow suspended multicore optical fibers with resonant microspheres containing gain media enables the realization of multiple laser functionalities within a single optical fiber. Figures 16(a–c) illustrate the schematic working principle of this multi-laser integration concept, as proposed by Wang P. F.'s research group¹⁰². In this specially designed hollow multicore optical fiber, the cores are suspended along the inner walls of the fiber, and the outer quartz cladding is only a few micrometers thick. This configuration results in a significantly enhanced evanescent field. The microsphere resonator achieves phase matching and energy coupling with the fiber core located on the inner wall of the fiber, transferring the evanescent field energy from the seed light source to the surface of the rare-earth-doped microsphere. This process facilitates the formation of whispering-gallery-mode resonance.

The light wave undergoes continuous total internal reflection along the inner surface of the rare-earth-doped glass microsphere embedded within the fiber, thereby being confined within the microsphere and propagating along its surface in a circular path. This mechanism enables signal amplification and gain generation. Ultimately, the resonant

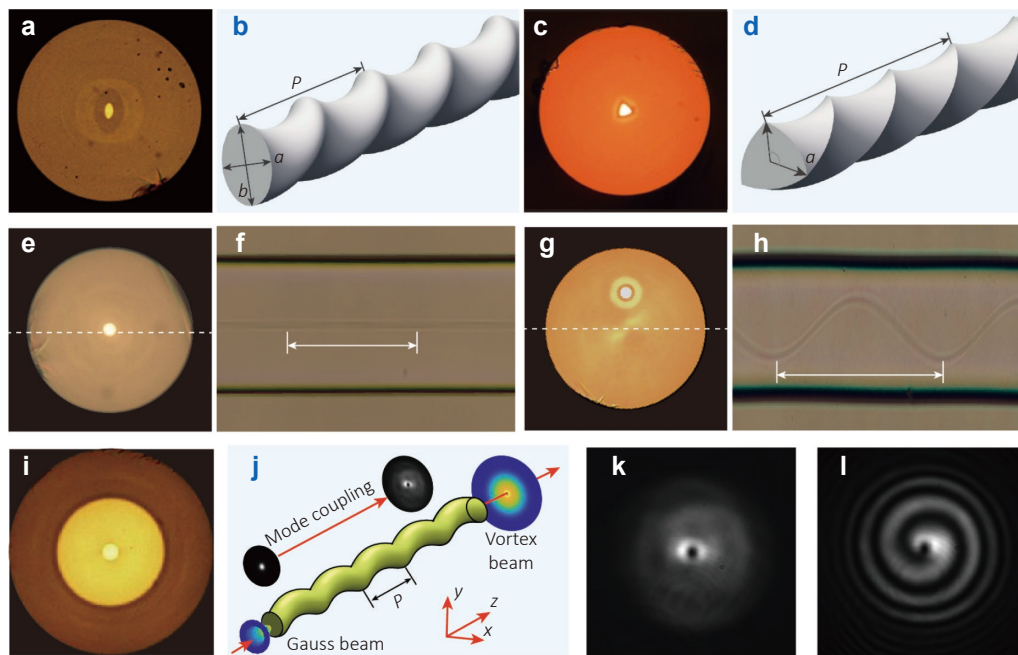


Fig. 14 | Illustration of three-dimensional helical-structured optical fiber device fabricated via heating and twisting. (a) End face of the elliptical-core optical fiber. (b) Twisted structure of the elliptical core. (c) End face of the triangular-core optical fiber. (d) Twisted structure of the triangular core. (e) End face with weak core offset. (f) Photographs showing slight central deflection. (g) End face with significant core offset. (h) Microscopic telecentric images of the helical structure. (i) Cross-sectional schematic of the double-clad optical fiber. (j) Schematic illustration of vortex beam generation. (k) Observed vortex mode pattern. (l) Interference results between the vortex beam and a Gaussian beam. Figure reproduced with permission from ref.⁸³, IEEE.

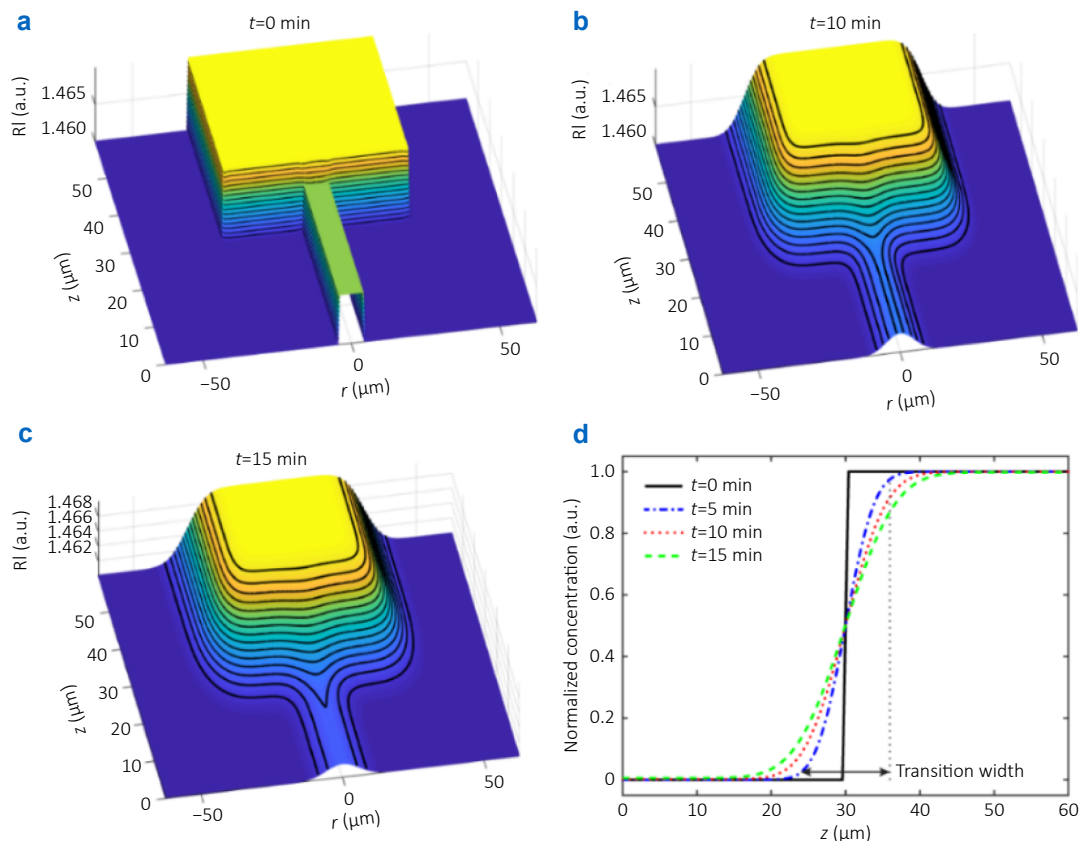


Fig. 15 | Three-dimensional light field control of refractive index waveguide within optical fiber achieved by thermal diffusion. This figure illustrates the evident radial and axial thermal diffusion occurring at the fusion interface between a standard single-mode optical fiber and a step-index multimode optical fiber. The thermal diffusion states are shown at different time points: (a) $t=0$ min; (b) $t=10$ min; (c) $t=15$ min. (d) The variation in the dopant concentration profile under varying thermal diffusion durations. Figure reproduced with permission from ref.⁸⁵, IEEE.

light is coupled out through the fiber core on the inner wall, achieving output with gain-enhanced characteristics.

This novel active microsphere resonant cavity device, based on hollow optical fiber technology, not only retains but also enhances the key optical properties inherent to traditional microresonant cavities: ultra-high optical quality factor (Q -factor), high energy density, ultra-narrow resonant linewidth, extremely small optical mode volume, and extended cavity ring-down time. Furthermore, the device enables three-dimensional spatial coupling between multiple fiber cores and a single microsphere resonant cavity. This allows multiple whispering-gallery modes to propagate along different paths on the same microsphere cavity surface, thereby offering the potential for fabricating microcavity lasers capable of multi-wavelength multiplexing within a single resonant cavity.

Figures 16(d, e) illustrate an all-pass and add-drop fiber device that integrates a hollow suspension dual-core fiber with a whispering gallery mode microsphere resonator, as proposed by Zhang X. B.'s research group¹⁰³. The device is fabricated by splicing a single-mode optical fiber with a suspended double-core hollow optical fiber, followed by

embedding microspheres into the structure. Most of the input light from the single-mode fiber is coupled into the two suspended cores of the hollow dual-core fiber. The coupling efficiency is influenced by the taper angle θ . When the taper angle and the core dimensions of the suspended double-core hollow fiber are appropriately balanced within the tapered region, the coupling efficiency achieves its maximum value. When microspheres of suitable diameter are symmetrically positioned, the coupler transitions from an all-pass configuration to a drop-type optical fiber device.

Three-dimensional optical fiber devices can be constructed by integrating inner-wall waveguide capillary optical fibers with resonant microspheres, as shown in Fig. 17. References^{105,106,108} proposed and demonstrated a conical hollow ring-core fiber coupler designed to excite the whispering-gallery mode (WGM) of embedded microsphere resonators.

This coupler is fabricated by splicing a hollow annular core optical fiber with a single-mode optical fiber, and its performance is further improved by reducing the cone angle at the tip of the splicing joint, thereby optimizing its

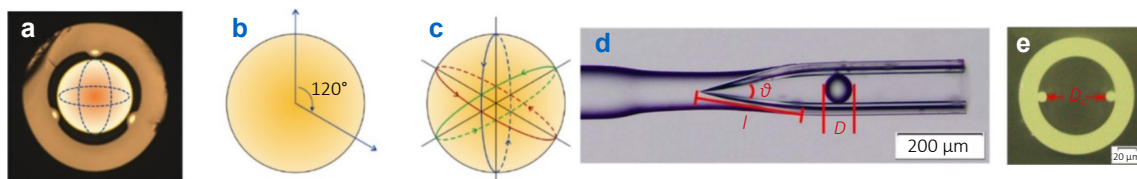


Fig. 16 | (a) Cross-sectional schematic diagram of the optical device of the hollow three-core optical fiber microsphere resonant cavity. (b) The internal angle between the suspended cores inside the optical fiber. (c) The propagation mode of the echo wall pattern on the microsphere. (d) Schematic diagram of whispering gallery mode microsphere resonator in suspended dual-core hollow optical fiber. (e) Cross-sectional view of hollow dual-core optical fiber. Figure reproduced with permission from ref.¹⁰³, IEEE.

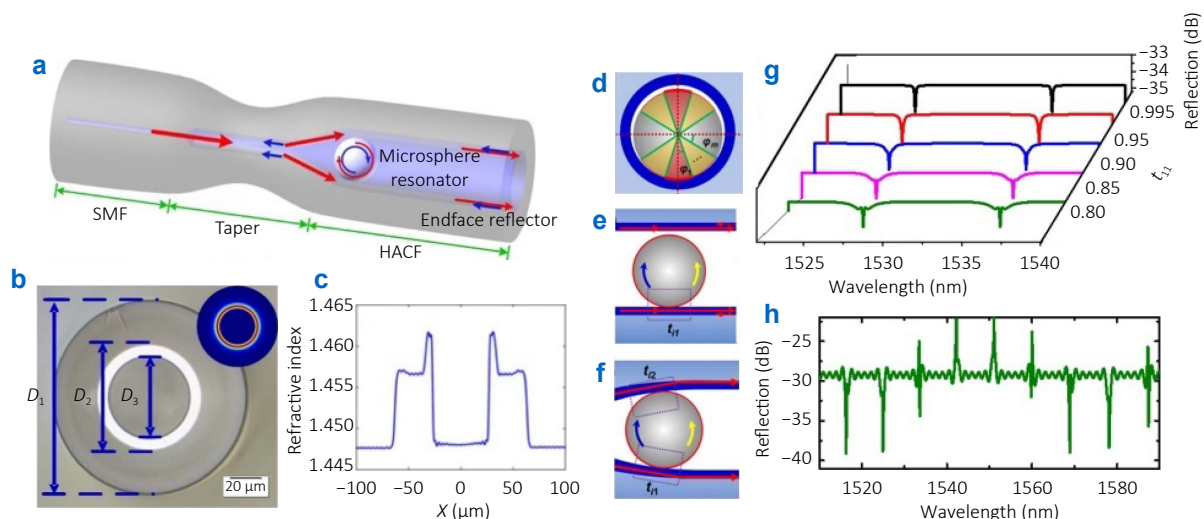


Fig. 17 | (a) Schematic diagram of a conical hollow annular core fiber-coupled microsphere resonator. (b) Cross-sectional view of hollow annular core optical fiber and illustration of its mode field distribution. (c) Refractive index profile of hollow annular core optical fiber. (d) Cross-sectional schematic diagram of the hollow annular core optical fiber embedded in the resonant microsphere model. (e) Microsphere coupling model not locked by hollow annular core optical fiber. (f) Microsphere coupling model locked by hollow annular core optical fiber. (g) The evolution of the reflection spectrum under (e) state. (h) Reflection spectra in state (f).

conical geometry. As a result, the coupling efficiency between the single-mode fiber and the hollow ring-core fiber is enhanced through evanescent field coupling, enabling the excitation of multiple WGM modes. By adjusting the size and position of the resonant cavity, both symmetric Lorentzian line shapes (positive and negative) and asymmetric Fano line shapes can be achieved. Notably, a contrast ratio as high as 58 was observed between high-quality (high-Q) and low-quality (low-Q) factor modes. This assembled three-dimensional optical device exhibits excellent thermal stability and demonstrates promising performance in temperature sensing applications¹⁰⁶.

L. Xu's research team developed a novel three-dimensional device system by integrating microbubble resonant structures with bi-tapered optical fibers, as illustrated in Fig. 18. The system employs low-refractive-index polymers to encapsulate the fiber taper-integrated microbubble resonators, where the polymer cladding functions as a protective matrix that effectively shields the coupling system from environmental disturbances. The encapsulation design is compact and exhibits excellent performance, maintaining a high Q factor over an extended period. Due to the hollow structure of the microbubble resonators, this packaging system demonstrates potential for practical applications in chemical and biomedical sensing^{108,109}.

Research on three-dimensional integration of optical fiber devices has advanced through multiple complementary approaches that enhance photonic functionality. Geometric structure mutation methods, including side-polished D-shaped fibers, end-face polishing, and post-welding etching, have enabled versatile platforms for sensors, modulators, and resonators, with recent breakthroughs in broadband all-fiber photodetectors and OCT imaging probes. Structure gradient techniques such as tapering and twisting exploit controlled deformations to induce mode coupling, supporting applications from long-period gratings and filters to high-efficiency vortex beam generators with broad spectral tunability. Refractive index gradient control, particularly via thermal diffusion, has matured into a robust method for fabricating isolators, couplers, interferometers, and sensors by tailoring mode fields without altering cladding geometry. Meanwhile, microdevice assembly

strategies that integrate microspheres, microbubbles, and hollow-core fibers have yielded ultra-high-Q whispering-gallery-mode resonators, multi-wavelength on-fiber lasers, and compact, stable platforms for chemical and biomedical sensing. Collectively, these approaches reflect a trend toward highly integrated, multifunctional microsystems that combine structural innovation, material engineering, and hybrid resonant coupling, with ongoing research focusing on improving reproducibility, robustness, and scalability to enable next-generation photonic communications, sensing, and biomedical technologies.

Functional expansion of three-dimensional integrated optical fiber devices: microfabrication technologies and material integration approaches

In the previous two sections, we primarily discussed the typical two-dimensional structural modifications and the diverse range of optical fiber devices enabled by three-dimensional structural innovations. In practical applications, however, the functionalities of optical fiber devices can be further enhanced through the application of microfabrication technologies and material integration strategies. In this section, we first present several notable studies on the functional expansion of three-dimensional integrated optical fiber devices. Subsequently, we provide detailed descriptions of the microfabrication techniques employed to enhance the performance of optical fiber devices. Finally, we introduce multi-material integrated optical fibers and the methodologies for combining various materials with optical fiber devices, respectively. These integration approaches enable optical fiber devices to exhibit a broader range of advanced functionalities.

Functional expansion of three-dimensional integrated optical fiber devices: selected inspirational contributions

In 2012, we elaborated on the development of fiber optic integrated optics, including fiber optic multi-waveguide integration, the fabrication of fiber optic functional

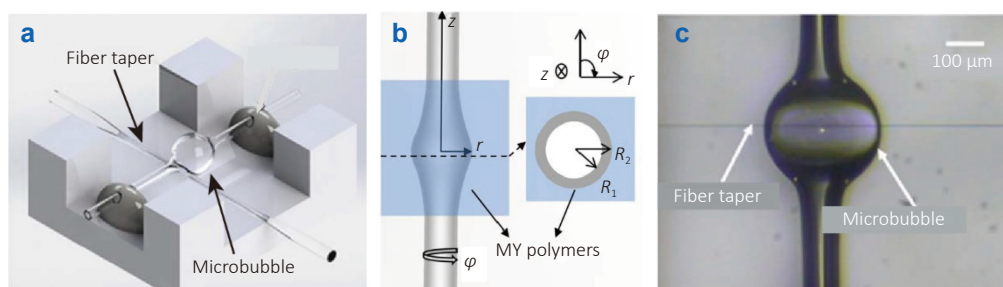


Fig. 18 | (a) Optimal coupling of the micro bubble resonator and the fiber taper in the air. (b) Illustration of a typical micro bubble resonator encapsulated in MY polymers. (c) Photograph of the micro bubble resonator coupling with a fiber taper, taken by a CCD camera. Figure reproduced from ref.¹⁰⁷, Optical Society of America.

components, and fiber optic interferometer technology. We summarized their characteristics and manufacturing methods and highlighted their significant potential in sensing applications¹¹⁰. Focusing on optical manipulation technology and its requirements, it was emphasized that integrating optical paths or components into a single optical fiber and utilizing in-fiber integrated optical technology can enable more convenient beam control and manipulation. This approach also provides a research platform for the interaction between light waves and microfluidic materials, offering promising prospects for a new branch of controllable photonic integration¹¹¹. Schmidt M. A. et al. proposed that the integration of novel materials into optical fibers enables the development of innovative in-fiber devices with unique functionalities¹¹², as shown in Fig. 19(a). This advancement not only enhances the application of fiber optics in key modern research domains such as bio-photonics, environmental science, optoelectronics, metamaterials, remote sensing, medicine, and quantum optics, but also broadens the developmental trajectory of fiber optic technologies.

Zakwan M. et al. indicated that fiber optic components based on distributed meandering waveguides can be widely applied in optical fiber communications, particularly in filters and delay line components, as well as in sensor components, due to their rich spectral responses. This versatility significantly enhances the performance of meandering waveguide components¹¹³. Liu Z. H. et al. proposed that by employing a $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST)-integrated non-volatile all-optical modulator, information control can be effectively achieved in fiber optic operations, thereby reducing energy consumption and laying a solid foundation for the development of all-optical equipment and networks¹¹⁴. Hua H. et al. demonstrated that integrating metasurfaces onto the end faces of optical fibers enables metafibers to serve as a crucial optical coupling platform in the fields of nanophotonics and fiber optics. Based on polarization-dependent plasmonic resonance, they designed and implemented all-fiber mode conversion metasurfaces with an efficiency of up to 21%. This achievement enabled high-purity circularly and Gaussian-polarized light output in fiber lasers, offering a reliable pathway for constructing next-generation all-fiber ultrafast structured laser

sources¹¹⁵, as shown in Fig. 19(b). Zhang L. et al. highlighted that electro-optic modulators (EOMs), which digitize optical signals through electric drive signals, have become essential components in modern optical communication systems. However, challenges such as high coupling loss, complex optical alignment, and single-band operation have prompted this study to integrate discrete EOM devices onto the end face of single-mode optical fiber patch cords for the first time. Utilizing ultrathin high-Q plasmonic metasurfaces, nano-fabrication-compatible and highly efficient electro-optic polymers, and coupling-free fiber optic interconnects, the study achieved dual-band operation (telecom O-band and S-band) and high-speed modulation (approaching 1 GHz at ± 9 V bias). This breakthrough opens new avenues for the realization of "plug-and-play" EOM devices and the deployment of ultra-compact "all-fiber" optical systems across multiple fields, including communication, imaging, and sensing¹¹⁶. Irannejad M. et al. emphasized that waveguide engineering based on nanoscale superlattice methods can overcome the structural compatibility limitations between Er^{3+} -doped tellurite glass and polydimethylsiloxane polymers in active-passive integration. This approach enables the effective utilization of fiber gain data and realizes waveguide amplification functions integrated with semiconductor pump sources¹¹⁷.

Wavelength tuning and spectral detection are realized through microstructure fabrication techniques

Rahnama A. et al. proposed that femtosecond laser irradiation in single-mode fibers could be utilized to create helical refractive index modulation, thereby effectively enhancing light scattering efficiency. Furthermore, spectral focusing was achieved through periodic tuning, enabling high-resolution spectral measurements without the need for lens-based recording systems. This advancement also facilitated the development of novel, compact photonic devices based on all-fiber spectrometers¹¹⁷. Black B. J. et al. introduced fiber optical tweezers technology, which, due to its compatibility with microfluidic systems, significantly deepened the physical and spectral analysis capabilities of micro- and nano-scale objects within microfluidic channels. Additionally, it enabled the rotational manipulation of such

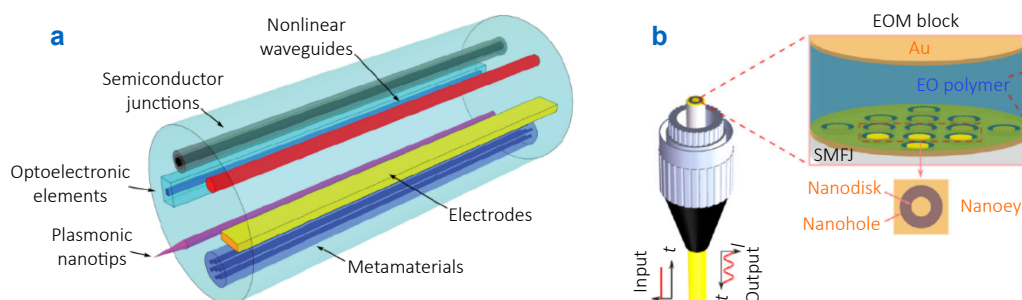


Fig. 19 | (a) The various functional elements and materials that can be integrated into fiber. (b) Schematics of configuration and nanofabrication of plasmonic meta-fibers for electro-optic modulators. The reflectance amplitude of optical signals can be modulated between "open" and "close" states by applying bias voltages. Figure reproduced from (a) ref.¹¹², John Wiley and Sons; (b) ref.¹¹⁸, Springer Nature.

objects, offering promising applications for lab-on-a-chip platforms and tomographic imaging¹¹⁹. Stoll A. et al. proposed an integrated spectrometer design based on coaxially connected optical fiber segments. The core component of this design is a compact helical beam composed of an $N \times N$ core array, which endows the spectrometer with inherent cross-dispersion characteristics in the transverse direction. This feature significantly improves spectral resolution while reducing optical loss. As a result, a resolution of 25 spectral channels can be achieved within a fiber cladding of merely 10 centimeters in length and 1 millimeter in diameter. Moreover, the inverse cone structure minimizes device loss and enhances wavefront overlap, capabilities that are not achievable in conventional planar spectrometers¹²⁰.

Metasurface integration and femtosecond microfabrication technologies are used for the functional expansion of devices

In order to integrate metasurface technology into optical fiber devices, Zhao Q. C. et al. proposed a novel approach by combining metasurface technology with optical fibers, thereby establishing a new platform referred to as "all-fiber" metasurface devices. This integration significantly broadens the application scope of optical fibers in various fields, including communication, sensing, imaging, and biomedicine, while also indicating a promising research direction for addressing the challenges associated with the fiberization of metasurfaces¹²¹. Maselli V. et al. introduced a method involving the amplification of femtosecond lasers through high-repetition-rate ytterbium fibers and the direct inscription of optical pathways within the fiber cladding. This innovation has led to the development of a new three-dimensional all-fiber optical routing technique, which substantially enhances the integration density of optical components. Furthermore, it facilitates the more efficient and compact fabrication of optical and optofluidic microsystems for applications in optical communication, sensing, and micro-fiber laboratories¹²². Fernandes L. A. et al. proposed a technique that integrates pre-modification methods with femtosecond laser direct writing to enable the fabrication of complex and integrated devices within the fiber cladding. This approach not only simplifies the assembly of optical components but also significantly enhances the system's stability and reliability. Consequently, it provides new opportunities for the integrated application of specialty fibers, such as photonic crystal fibers¹²³.

Integration of multi-material co-stretching: expanding quartz optical fibers to multifunctional fibers based on various materials

Since the MIT fiber group led by Fink Y. successfully developed multi-material photonic bandgap (PBG) fibers with hollow cores and all-solid cladding for the first time¹²⁴, the

rapid advancements in PBG fibers have significantly influenced the fiber manufacturing process itself. One notable outcome has been the introduction of the concept of "multi-material optical fibers". This novel class of fibers leverages the manufacturing techniques and technologies traditionally used for optical fibers. By modifying the material composition of these fibers, new structural designs, functionalities, and applications have been enabled.

Multi-material fibers are defined as high-aspect-ratio structures composed of multiple distinct materials, typically fabricated through the thermal drawing of larger-scale precursor structures known as "preforms". Materials exhibiting diverse optical, electronic, thermomechanical, and acoustic properties can now be integrated into such fiber architectures¹²⁵. The fabrication process of integrated optical fiber devices based on preform rods is shown in Fig. 20¹²⁶. The innovative fabrication techniques developed in this emerging field have led to the creation of optical fibers with novel functionalities that differ significantly from those of conventional optical fibers. Examples include fibers that generate electrical signals in response to light incident on their outer surfaces^{127,128} or changes in ambient temperature; self-monitoring fibers capable of assessing their own structural integrity¹²⁹; lightweight and flexible fibers capable of imaging the surrounding environment¹²⁵; fibers capable of transmitting or detecting acoustic signals¹³⁰; and fibers that actively modulate their optical properties through integrated microfluidic channels¹³¹. Consequently, fiber drawing is evolving into a fabrication methodology for producing photonic and optoelectronic devices with such fiber-based architectures, which can be integrated or woven into textiles to impart advanced functionalities.

With the advancement of multi-material fiber manufacturing technologies, new perspectives on the fiber drawing process itself have emerged. By reducing the feature sizes—down to the nanoscale—nanowires with diameters of only a few nanometers and exceptional lengths can be fabricated using this approach¹³². In this context, the fiber cladding can be viewed as a reaction chamber for chemical synthesis, while thermally responsive coatings can act as catalysts, facilitating chemical reactions between reagents placed within the preform¹³³. Furthermore, multi-material fibers offer a novel platform for investigating controlled fluid dynamics in confined spaces over extended lengths.

The emerging revolution in multi-material optical fiber technology is primarily manifested in two key aspects of fiber manufacturing. First, the process typically begins with the preparation of macroscopic preforms. Because these preforms are constructed at a larger scale, complex cross-sectional geometries can be directly engineered, and the spatial arrangement of different materials can be precisely controlled. Second, hot-melt fiber drawing is an inherently scalable and continuous manufacturing process that enables the production of ultra-long fibers with high dimensional and axial uniformity. To preserve the intricate transverse

architecture of the multi-material preform and ensure that all constituent materials flow uniformly at the same drawing temperature, certain constraints are imposed on the selection of compatible material combinations.

In addition to conventional preform fabrication techniques, several novel approaches have been developed. For instance, multi-material fibers can be fabricated by using single-material fibers or wires as structural scaffolds, followed by additive manufacturing processes. Alternatively, new functional fiber preforms can be created by applying coatings onto the outer surfaces of pre-stretched preforms¹³⁴, or by employing vapor deposition techniques within the central air cavities of shorter preforms¹³⁵.

Material-based integration enhances the functionality and improves the sensing sensitivity of devices

The integration of two-dimensional materials with optical fiber devices can significantly enhance or expand the functionalities of conventional optical fiber systems. Cusano et al. proposed that by incorporating functional materials at micro- and nano-scale locations within optical fibers, the capabilities of fiber-optic sensing can be extended, giving rise to the concept of "lab on fiber technology". This concept has been further categorized into three distinct paradigms: "lab on tip", "lab around fiber", and "lab in fiber", as shown in Fig. 21(a). The advancement of this technological framework holds substantial potential for advancing biosensing applications¹³⁶.

In terms of practical implementation, Dong L. P. et al. demonstrated that by integrating a graphene/polymethyl methacrylate (PMMA) hybrid film onto a core-free side-polished fiber (CSPF), a fully integrated fiber-based electro-optical prototype device could be realized. This device

enables electro-optical modulation through the synergistic effects of lossy mode resonance (LMR) and the electro-optical thermal effect, thereby significantly reducing fabrication complexity and cost. This approach offers a novel strategy for the design of multi-functional all-fiber devices in the fields of optical communication and sensing¹³⁷, as shown in Fig. 21(b). Zhu C. et al. highlighted that fiber-optic extrinsic Fabry-Perot interferometers (EFPIs) have achieved considerable progress over the past two decades due to the integration of fiber waveguide technology with advanced microfabrication techniques. These devices have been widely adopted across various domains, enabling flexible and diverse designs for EFPI sensors tailored to different physical parameters, thereby significantly advancing high-sensitivity sensing technologies¹³⁸. Tabassum S. et al. reported that by fabricating a polymer nanoarray on the tip of an optical fiber and coating it with titanium dioxide, combined with a copper(I) complex layer and a controllable heating element, a highly sensitive and selective ethylene gas sensor was developed. This innovative sensing platform enables effective monitoring of banana ripening and senescence, significantly improving the sensitivity and selectivity of ethylene detection¹³⁹, as shown in Fig. 21(c). Holmes C. et al. noted that by reducing the Young's modulus of doped silica materials, flexible planar sensors can be more effectively integrated into fiber-reinforced polymer composite structures, thereby expanding their applicability across a broader range of engineering applications¹⁴⁰. Naderi N. et al. proposed that by fabricating a metal-semiconductor-metal photodetector on the curved surface of an arc-shaped optical fiber and employing a PMMA layer to enhance light-semiconductor nanostructure interactions, an all-fiber photodetector based on zinc oxide nanostructures can achieve enhanced photon absorption and

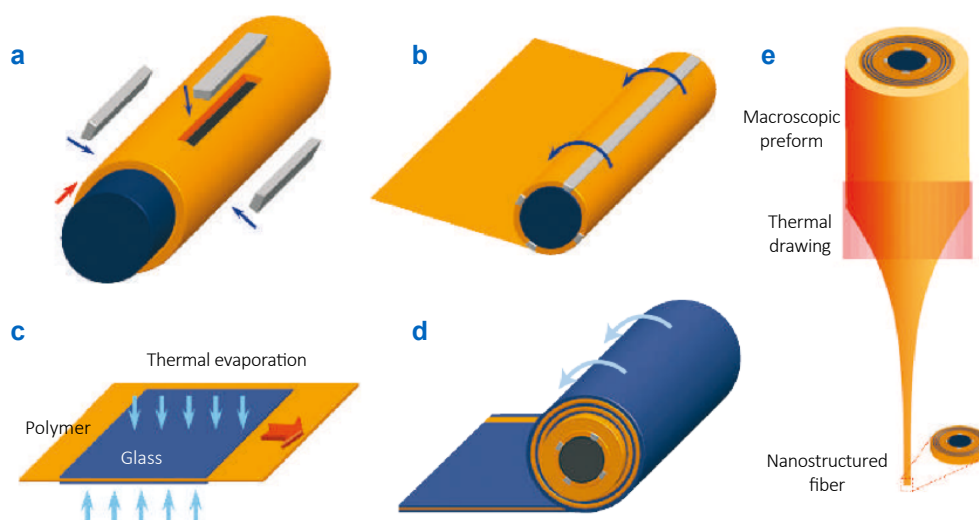


Fig. 20 | Preform-based fabrication of integrated fiber devices. (a) A glass rod is assembled with shell and four metal electrodes. (b) A polymer sheet is wrapped around the structure to form a protective cladding. (c) High-refractive-index glass is evaporated onto both sides of a thin, low-refractive-index polymer film. (d) This is then wound onto the preform. (e) The preform is consolidated in a vacuum oven and is thermally drawn to fibers. Figure reproduced from ref.¹²⁶, Springer Nature.

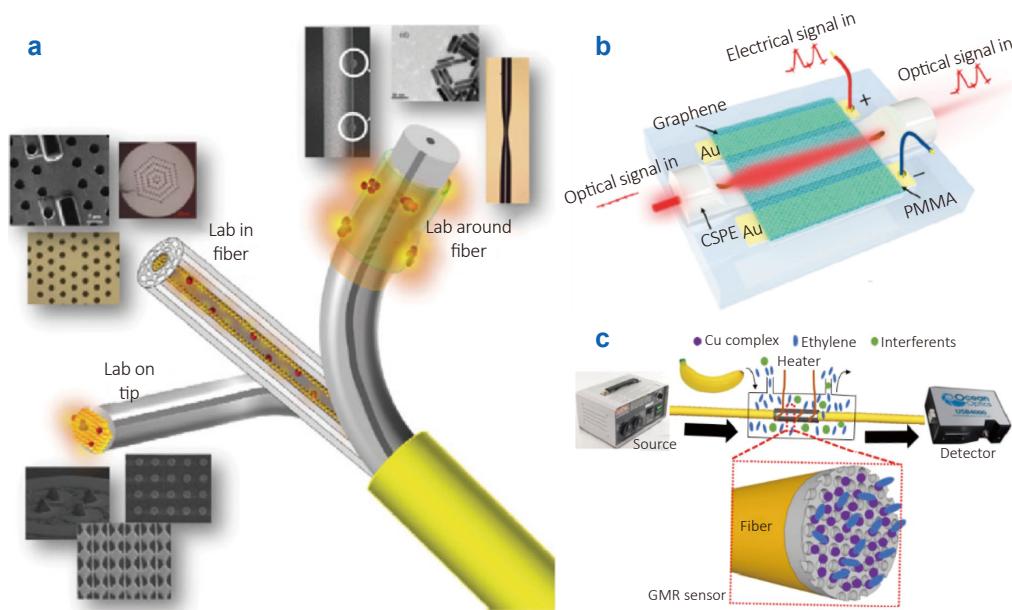


Fig. 21 | (a) "Lab on Fiber Technology" is classified into three main paradigms: lab on tip, lab around fiber, and lab in fiber. (b) Schematic diagram of the as-fabricated graphene coreless side-polished fiber all-fiber device. (c) Nanopatterned fiber-tip guided mode resonance device for selective detection of ethylene. Figure reproduced from: (a) ref.¹³⁶, John Wiley and Sons; (b) ref.¹³⁷, American Chemical Society; (c) ref.¹³⁹, IEEE.

photocurrent generation, significantly improving photodetection performance³⁷. Wang C. et al. demonstrated that doping $\text{Eu}(\text{DBM})_3\text{Phen}$ into PMMA polymers and exciting with a blue LED enables efficient energy transfer between organic ligands, facilitating a transition from the D-5(0) to the F-7(3) energy level of Eu^{3+} ions, thereby significantly enhancing the relative gain of the polymer waveguide amplifier. This development opens new possibilities for the practical realization of optical integrated system chips¹⁴¹. Zhou P. et al. indicated that advancements in coherent beam combining technology for fiber lasers have led to increased output power and expanded application diversity, demonstrating significant value in both fundamental scientific research and industrial processing applications¹⁴².

The current state of research on three-dimensional integrated optical fiber devices demonstrates a strong momentum toward enhancing functionality through microfabrication technologies and material integration approaches. Recent progress highlights the integration of metasurfaces, femtosecond laser microfabrication, and nanoscale waveguide engineering as pivotal techniques for expanding device performance in communication, sensing, imaging, and biomedicine. These advancements enable wavelength tuning, high-resolution spectral detection, and compact all-fiber routing systems while addressing long-standing challenges of alignment, coupling, and scalability. Parallel to this, the emergence of multi-material fibers fabricated via thermal drawing and hybrid processes has transformed fibers into multifunctional platforms, incorporating diverse optical, electronic, acoustic, and microfluidic properties. Integration of novel materials—such as graphene, $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST), electro-optic polymers, and 2D nanos-

tructures—has further pushed the boundaries of sensing sensitivity, electro-optic modulation, and all-fiber photodetection. Collectively, these developments indicate a paradigm shift where optical fibers evolve beyond passive light transmission into active, multifunctional, and miniaturized optoelectronic systems, paving the way for applications in quantum technologies, smart textiles, lab-on-fiber biosensing, and next-generation communication networks.

Summary and future outlook

In this article, we review the emergence and application of three-dimensional integrated optical devices. Optical fibers can be classified into various types based on their structure and function. There are also numerous micro-nano processing techniques that locally process optical fibers, and new functional materials can be integrated in the processed device area. The combination of these different dimensions has resulted in a wide variety of three-dimensional integrated optical devices with diverse functions. Since optical fibers are made of quartz, which has very stable physical and chemical properties, their durability is guaranteed. Although some micro-nano processing techniques may reduce the mechanical strength of the integrated optical fiber devices, appropriate packaging structures usually can solve this problem. For example, metal sleeves, highly stable and highly mechanical-strength adhesives can be used to encapsulate and protect the devices.

The preparation and feasibility of the functions of these three-dimensional integrated devices have been verified in relevant literature. However, in the actual large-scale application process, it is necessary to develop reliable, stable, and batch-producing micro-processing equipment for these

devices, such as fiber end lens polishing equipment, D-type optical fiber device preparation equipment, and drawing equipment for multi-functional integrated medical optical fibers. It has been mentioned in the references^{35,65} that the related manufacturing equipment has been commercialized. As for the manufacturing cost of these three-dimensional integrated optical fiber devices, it actually depends on the market. Once the demand market forms a certain scale, the manufacturing cost of the devices will be greatly reduced.

To summarize, based on the intrinsic properties of optical fibers and with the support of various auxiliary technologies and methods, it has been realized to integrate multiple three-dimensional devices and components onto optical fibers. The integration of multiple functional elements through optical fiber processing technology is particularly promising for the following areas of development and application:

1) Achieving miniaturization of three-dimensional optical devices. This facilitates the integration of compact optical components into micro-optical system modules that can be embedded within various application systems.

2) Acting as distributed sensing units, optical fibers are capable of acquiring vast amounts of data. Additionally, they inherently share a transmission channel with conventional optical communication systems, thereby enabling the integration of communication and sensing functionalities

within a unified system.

3) Utilizing the flexibility of optical paths allows not only for interconnection between two-dimensional chip systems but also for the embedding of fiber-integrated optical components within such systems. This enables signal coupling, preprocessing, and transmission, thereby expanding the possibilities for optoelectronic hybrid chip integration.

4) Integrating multifunctional optical components into a slender optical fiber opens up new opportunities for biomedical applications. For example, in clinical medical practice, minimally invasive interventional instruments require extremely compact dimensions. Therefore, optical systems integrated within a single optical fiber can significantly enhance the functionality of such devices, enabling the development of novel diagnostic and therapeutic tools. This highlights the vast potential of advanced optical fiber applications in medical scenarios, as illustrated in Fig. 22³⁵.

Looking ahead, the development and evolution of optical fiber technology, akin to biological evolution, has progressed from simple one-dimensional structures to more complex three-dimensional configurations, continuously incorporating diverse functionalities to address individualized needs. The multifunctional integration of optical fibers represents an interdisciplinary domain encompassing optics, materials science, device physics, nanotechnology, and fluid dynamics. Although this field is still in its infancy,

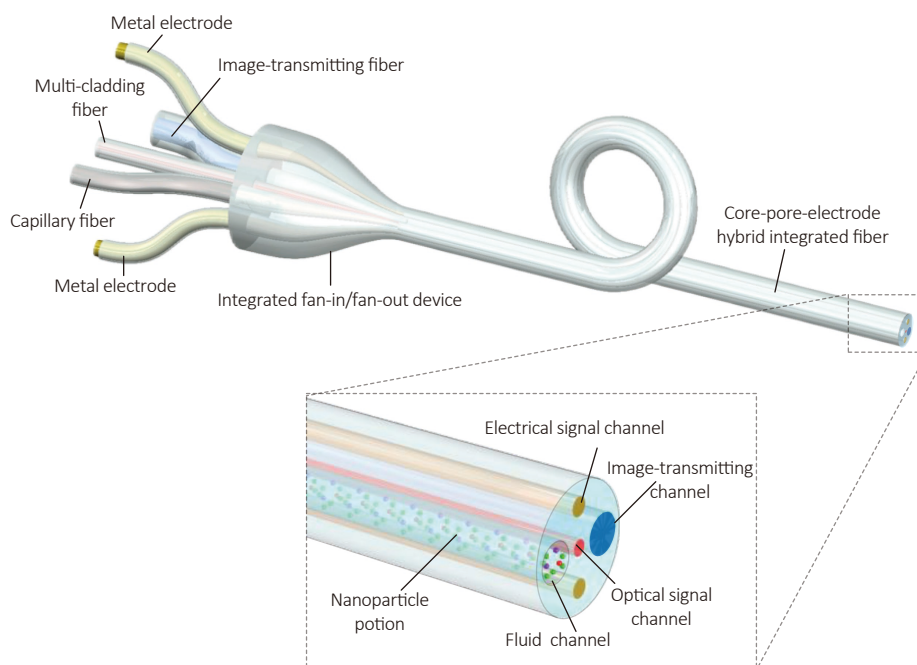


Fig. 22 | A schematic diagram of a multifunctional modular optical fiber probe applicable in the medical field, capable of integrating "sensing-measurement-diagnosis-therapy" functionalities on a single optical fiber. This probe assembly consists of a multifunctional optical fiber and a fan-in/fan-out device. The multifunctional optical fiber integrates an electrical signal transmission channel (metal electrode), an optical signal transmission channel (light waveguide), a microscopic image transmission channel (multimode core waveguide), and a micro-liquid/drug delivery channel (micro-hole structure). The integration of these channels enables the fiber probe to perform multiple composite functions in interventional medicine. The fan-in/fan-out device, fabricated through integrated drawing of the multifunctional optical fiber, serves to separate and manage these functionally distinct channels, thereby facilitating their independent operation and integration. Figure reproduced with permission from ref.³⁵, CLP.

it has begun to demonstrate promising and attractive prospects. To illustrate its potential, the following two representative application scenarios are presented as indicative of the vast possibilities for future applications.

In the realm of scientific research and experimentation, a rapidly emerging application scenario involves the development of the so-called "lab on/in fiber". Optical fibers inherently possess optical waveguide channels, which have prompted researchers to explore the integration of various materials—such as inorganic, organic, and biological substances, nonlinear optical materials, and even microorganisms like viruses, cells, and bacteria—into the end face or side surface of the fiber. This enables direct interaction between light and matter within the fiber structure, with measurement results subsequently transmitted through the optical channels of the fiber. This concept has seen rapid development^{4,143}, as the micro- and nano-scale dimensions of optical fibers facilitate strong light-matter interactions. This characteristic is particularly advantageous for conducting experiments on the interaction between light and biological or micro-scale living materials. Consequently, fiber-integrated laboratories offer a highly promising micro-experimental platform for interdisciplinary research.

Another notable application scenario lies in the healthcare field. As research into the biomedical applications of optical fiber technology continues to advance, the demand for specialized fiber functionalities is steadily increasing. In addition to traditional optical channels used for sensing and transmitting optical signals, there is a growing need for integrated microfluidic channels capable of facilitating microfluidic liquid delivery and body fluid collection¹⁴⁴. Furthermore, there is interest in incorporating electrode functionalities that enable the acquisition of electrical signals or the delivery of electrical stimulation. For practical implementation, there is a strong push to integrate all or some of these functionalities onto a single optical fiber. By integrating optical fibers with various functional devices—such as combining microfluidic systems with optical fiber components—the overall functionality of the system can be enhanced, enabling shared optical sensing and fluid transmission systems. However, such multifunctional optical fibers still require compatible bundled devices to interface with independent single-function systems in order to realize their respective capabilities and achieve overall functional enhancement. This remains a key challenge in the development of next-generation multifunctional optical fibers, as illustrated in Fig. 22.

The successful development of specialized multifunctional integrated optical fiber probes^{35,65} marks a significant milestone in the evolution of optical fiber technology, particularly in the context of minimally invasive interventional sensing, microscopic imaging, targeted light delivery, and photodynamic therapy. The ability to perform microscopic imaging in previously inaccessible or extremely narrow anatomical regions has opened new frontiers in the

advancement of critical medical technologies, ranging from neurosurgery to vascular diagnostics. This innovation holds profound implications for the advancement of fundamental neuroscience research and the development of novel therapeutic strategies for neurological disorders, offering innovative tools for exploring the frontiers of biomedical science.

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Competing interests

The authors declare no competing financial interests.



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