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Specialty active fibers for fiber-optic sensing networks: from gain media to active sensing units

Zhexu Huang¹, Yao Li¹, Jiayi Wan¹, Yanhua Luo^{1*}, Jianxiang Wen¹, Fufei Pang¹, Tingyun Wang¹ and Gang-Ding Peng²

Abstract: As the Internet of Everything (IoE) continues to connect physical objects, sensing units, and information systems, traditional passive optical fibers face practical limitations in some large-scale and complex sensing networks, particularly regarding signal-to-noise ratio (SNR) degradation and limited system integration. By enabling in situ high-fidelity signal excitation and online gain compensation, rare-earth-doped specialty active optical fibers provide routes to local signal generation and gain compensation, which may help mitigate these limitations in selected sensing-network architectures. This paper summarizes recent advances in specialty active fibers through three interrelated routes: material composition, waveguide design and emerging digital manufacturing. First, material and matrix engineering can partly mitigate host-glass limitations through advanced deposition processes and multi-ion designs, thereby improving gain-band coverage and luminescence stability under specific conditions. Second, at the microstructural design level, active fibers exploit engineered microstructures to provide additional degrees of freedom for optical-field manipulation. This not only helps address modal gain equalization in space-division multiplexing but also enhances evanescent field interactions, providing a structural foundation for cross-sensitivity decoupling in multiparameter sensing and the generation of spatially structured light. Finally, emerging additive manufacturing, especially 3D printing, enables spatial customization of active components and micro- to nanoscale lab-on-fiber integration, enabling more flexible design of sensing units for targeted multiphysical responses. This review also discusses key bottlenecks to deployment. These include parasitic absorption caused by residual hydroxyl and carbon-containing species, as well as scattering associated with pores and interfacial defects in additively manufactured fibers. Looking forward, large-scale fiber-optic sensing networks may benefit from integrating active gain, tailored waveguides and local sensing functions in the same fiber platform. Together, these technological routes show how active fibers are evolving from conventional gain media toward active sensing units that couple environmental transduction with local photonic functions, including signal generation, amplification and optical-field control.

Keywords: specialty active fibers; fiber-optic sensing networks; active fiber sensors; optical-field manipulation

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1 Introduction

As the Internet of Everything (IoE) extends connectivity from information systems to physical objects and sensing units, fiber-optic technologies^{1–3} move toward long-haul transmission, high-sensitivity sensing⁴, and large-scale networking, while their roles are expanding from passive

transmission to active signal generation, conversion, and amplification⁵. Optical fibers have evolved from passive transmission media into active photonic carriers capable of energy delivery^{6,7}, signal conversion⁸, and optical amplification⁹. While conventional passive fiber-sensing technologies have reached a high degree of maturity, their deployment in complex, large-scale sensing networks remains

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constrained^{10–12}. Specifically, transmission losses degrade the signal-to-noise ratio (SNR) in long-haul links, while the reliance on bulky external pump and signal-source modules limits system integration and constrains the ultimate detection limit. In industrial and extreme environments, these constraints are compounded by the need for high-fidelity signal excitation, remote gain compensation, and integrated optical sensing functions¹³. To address these challenges, rare-earth-doped specialty active fibers¹⁴ have emerged as promising components for sensing networks that require local signal generation, optical amplification or integrated transduction. These fibers are generally fabricated by incorporating rare-earth ions¹⁵, such as erbium (Er³⁺), ytterbium (Yb³⁺), and thulium (Tm³⁺)¹⁶, into silica or multicomponent glass matrices. The resulting active media support stimulated emission and can therefore provide laser oscillation and optical amplification.

Within sensing networks, this material platform supports two complementary roles. First, active fibers can operate as conventional gain media in laser sources and in-line amplifiers¹⁰. In these configurations, they generate coherent and broadly tunable probe signals¹⁷ or compensate for propagation loss, thereby improving the signal-to-noise ratio over long links. Second, active fibers can function directly as sensing elements. Fiber-laser sensors¹⁸, including distributed Bragg reflector and distributed feedback configurations, convert external perturbations into changes in their laser output. Active interferometric sensors¹⁹ based on Mach–Zehnder interferometer (MZI) or Fabry–Pérot interferometer (FPI) architectures similarly encode temperature, strain or vibration in their optical responses. These configurations enable high-resolution measurements in point and quasi-distributed sensing schemes.

These complementary roles allow specialty active fibers to occupy several functional positions within a fiber-optic sensing system. A typical system comprises an interrogation source, an optical link containing one or more sensing elements, a photodetector and a signal-processing unit, with coupling, multiplexing, filtering or amplification modules as required. Within this architecture, an active fiber may serve as the interrogation source, an in-line amplifier, a sensing element or an integrated unit that combines sensing with local generation or amplification. The appropriate configuration depends on system-level deployment requirements. Increasing node density raises accumulated splitting, insertion and propagation losses, thereby changing the required link margin and local gain. The required sensitivity depends on measurand resolution, detector noise, interrogation bandwidth and calibration uncertainty, whereas the achievable update rate depends on the response times of the sensing element, interrogation system and signal-processing stages. Power consumption and cost are further influenced by pump sharing, component count, splicing, packaging and manufacturing yield. Consequently, no universal threshold of sensitivity, gain, or loss applies to all Internet of Things

(IoT) application scenarios. For an amplification function, the active fiber must offset the relevant link losses without introducing unacceptable noise or saturation. For a sensing function, its response must meet the required resolution and update rate within the available power and cost budgets. An integrated active sensing unit must satisfy the requirements for both environmental transduction and its intended local active photonic function.

The integration of sensing and amplification functions simplifies the physical-layer architecture of the network while improving both detection precision and range. This dual capability is particularly advantageous in large-scale fiber-optic sensing networks that connect distributed sensing units with information systems. In these sensing networks, a sensing unit is expected not only to transmit optical signals but also to generate and amplify them locally, transduce external stimuli into optical responses, and regulate the optical field when needed. To clarify this transition from gain media toward active sensing units, we review recent advances in active optical fibers along three technological routes. Composition and host-matrix engineering provide the materials basis by improving gain efficiency, accessible spectral windows and environmental robustness. Microstructured waveguide engineering addresses optical-field distribution and enhances sensitivity by tailoring modal overlap, polarization, orbital angular momentum (OAM) modes, and evanescent-field interactions. Additive manufacturing^{16,20,21} extends this evolution toward spatial customization by enabling freeform placement of functional materials and lab-on-fiber integration. Together, these routes clarify how active fibers could evolve from conventional gain media toward active sensing units with integrated gain, optical-field control and sensing capabilities. In this review, an ‘active sensing unit’ denotes an active-fiber-based functional segment that combines environmental transduction with at least one local active photonic role. This role may involve signal generation, optical amplification, spectral conversion or optical-field control. The active and sensing functions may be co-located within one fiber segment, or the same specialty active fiber may fulfill two roles within a sensing system. By contrast, a conventional gain medium is designed primarily to convert pump energy into optical emission or amplification and may remain functionally separated from the sensing element. The distinction is therefore functional rather than purely material: an active sensing unit participates in both measurement and local signal management. Table 1 summarizes the functional distinction between conventional gain media and active sensing units.

2 Evolution of specialty active optical fibers

To address the complex demands of modern sensing architectures, the development of active fibers has focused on enhancing gain characteristics and optimizing structural

Table 1 | Functional distinction between conventional gain media and active sensing units.

Aspect	Conventional gain medium	Active sensing unit
Primary function	Optical emission or amplification ^{15,17,43}	Environmental transduction combined with one or more local active photonic functions ^{18,68,98}
System role	Source or amplifier element	Integrated sensing and local signal-management element
Structural design	Optimized primarily for pump absorption, signal-mode overlap and gain performance ^{22,44,77}	Designed to coordinate active-material distribution, modal fields and measurand interaction ^{86,89,98}
Manufacturing priority	Low loss, gain efficiency, spectral coverage and stability ^{16,26}	Functional integration, geometry control, packaging compatibility and reproducibility ^{108,110,113}
Typical system-level metrics	Gain, output power, bandwidth, noise figure, saturation power and pump efficiency	Sensitivity, resolution, cross-sensitivity, response time, sensitivity-matrix condition number (where applicable), link margin and power consumption

designs. This section reviews these advances across three linked routes, moving from composition-engineered active fibers to microstructured active fibers and finally to 3D-printed active fibers. As illustrated in Fig. 1, these routes organize the discussion from host materials to waveguide structures and manufacturing approaches. Within this framework, composition-engineered active fibers, including conventional single-doped and multicomponent co-doped systems, represent the most established route. Single-doped fibers provide the basis for high-quality laser emission in specific wavelength bands, such as those centered at 1.0, 1.5, or 2.0 μm band. In contrast, multicomponent co-doped fibers —exemplified by $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doping²²—improve pump absorption cross-sections and energy conversion efficiency through inter-ionic energy transfer, thereby helping maintain signal quality in remote or multiplexed sensing links. Microstructured active fibers leverage photonic crys-

tal or multi-core architectures to achieve precise control over mode-field distributions and nonlinear behavior. Such control can reduce specific nonlinear or modal impairments in selected links and can broaden the design space for multi-parameter sensing. Furthermore, 3D printing can relax some material-compatibility and geometric constraints associated with traditional preform-drawing processes. This additive approach enables the spatial gradient distribution of rare-earth dopants and the flexible design of complex multi-core structures.

Figure 1 summarizes this framework through three complementary design dimensions. Composition engineering controls the host matrix, dopant species and energy-transfer processes. Microstructural engineering regulates modal distributions and optical-field interactions. Additive manufacturing extends this control to digitally defined geometries and customized sensing units. These routes are

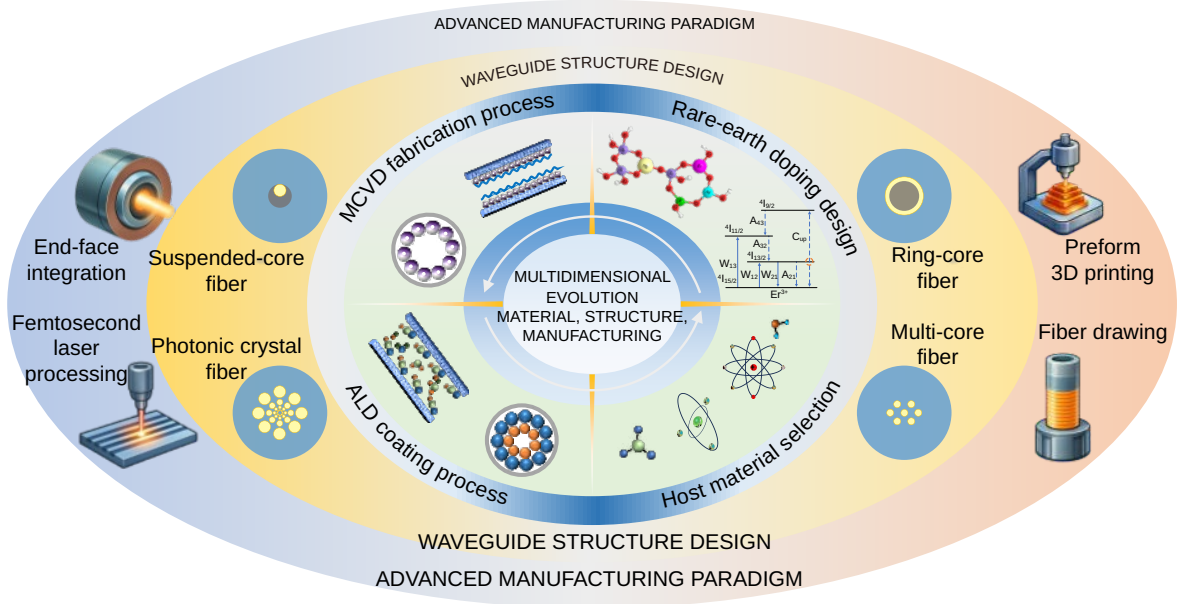


Fig. 1 | Evolution of active optical fibers across material, waveguide and manufacturing routes.

not strictly sequential; instead, they increasingly converge through the coordinated design of active materials, waveguide structures and manufacturing processes. The following sections examine how each dimension contributes to the progression from gain media toward active sensing units.

2.1 Composition-engineered active fibers: matrix design and energy conversion

Composition-engineered active fibers represent the most established route for providing optical gain, supporting lasing, and enabling emission-based sensing functions. Regardless of the configuration—ranging from single- to multi-element doping—the laser output and sensing performance of active fibers are primarily governed by the energy-level transition characteristics of the dopant ions and their distribution profiles within the host matrix. Manufacturing techniques such as modified chemical vapor deposition (MCVD)²³, plasma chemical vapor deposition (PCVD)²⁴, and sol-gel methods²⁵ enable precise control over the rare-earth concentration profile²⁶ within the fiber core. Such control over the dopant concentration profile strongly influences key performance metrics, including gain bandwidth, output power, and thermal stability. Active doping systems generally fall into two primary categories:

- **Single-doped fibers:** By leveraging the three- or four-level transition systems of specific rare-earth ions, these fibers provide the necessary gain for sensing signals within designated wavebands. They can also utilize amplified spontaneous emission²⁷ (ASE) to function as broadband sources or as seed sources for narrow-linewidth laser emission. For instance, the high gain of erbium-doped fibers²⁸ (EDFs) makes them widely used for signal amplification in long-haul fiber systems and relevant sensing links²⁹.

- **Multi-doped fibers:** By utilizing energy transfer mechanisms from sensitizer ions (e.g., Yb³⁺/Er³⁺ co-doping)³⁰, these fibers enhance energy conversion efficiency and broaden the gain spectrum. This synergistic design improves pump utilization and compensates for cascaded losses in multi-node multiplexed networks. Consequently, co-doping provides a promising approach for active fibers used in remote or multiplexed sensing links.

2.1.1 Single-doped fibers: spectral extension and durability

Since the first realization of stimulated emission in Nd³⁺-doped fibers³¹ in the 1970s, single-element doping systems have remained fundamental to active fiber technology. By introducing various rare-earth and other metal species, broad gain spectra covering the visible to mid-infrared (mid-IR) ranges have been achieved. Specifically, terbium (Tb³⁺) and praseodymium (Pr³⁺)-doped fibers²⁹ enable high-resolution biochemical sensing in the visible spectrum. In the near-infrared (NIR) region, Er³⁺-doped fibers² support

telecom-grade, wide-area sensing networks, while Yb³⁺-doped fibers³² offer high pump absorption efficiency and power-handling capabilities. Extending to longer wavelengths, thulium (Tm³⁺)-doped fibers³³ provide broadband gain in the 2 μ m window, and holmium (Ho³⁺)-doped fibers³³ are utilized for mid-IR environmental monitoring and molecular fingerprint identification. Collectively, the development of these materials enables the construction of high-performance fiber-based light sources, optical amplifiers, and sensors.

Driven by the stringent requirements for signal quality and system integration in sensing networks, recent research on single-doped fibers has increasingly addressed silica-matrix limitations related to dopant loading, spectral response and environmental durability. First, at the fabrication level, the introduction of atomic layer deposition (ALD)³⁴ enables atomic-level control over the spatial distribution and size of nanoscale active species (Fig. 2(a–c)). For example, Wang et al.³⁵ utilized ALD to achieve size-controlled doping of PbS quantum dots within silica fibers. By tailoring quantum confinement, they obtained ultra-broadband gain spanning from 1050 to 1350 nm, with a gain flatness better than 3.2 dB. Building on this, they³⁶ integrated ALD with the conventional MCVD technique to prepare bismuth-doped silica fibers (BDSFs). By tailoring the silica glass network at the atomic scale, they engineered specific Si-related defect sites to activate emission centers, achieving a significant enhancement in fluorescence intensity centered in the E-band (~ 1420 nm). Moreover, to address the limitations of low solubility and the resultant quenching of rare-earth ions within silica matrices, Wang et al.³⁷ combined density functional theory (DFT) calculations with ALD fabrication to establish a Tb–O–Al atomic-level coordination environment in Tb/Al co-doped silica optical fibers. Their study demonstrated that precise control over the spatial distribution of active layers and co-dopants effectively suppresses concentration quenching while enhancing the magneto-optical properties of the material. This provides useful guidance for developing fiber-based magnetic-field sensors with improved sensitivity.

Beyond deposition techniques, expanding the host matrix systems and refining melting processes are critical strategies for overcoming solubility limits and developing active fibers for specialized wavebands. To meet the demand for coherent visible light sources, Luo et al.³⁸ utilized a double-clad praseodymium (Pr³⁺)-doped ZBLAN fluoride fiber. By leveraging the highly efficient energy-level transitions within this low-phonon-energy host, they achieved a direct red laser output at 635 nm. In the longer-wavelength regime, Leich et al.³⁹ fabricated high-alumina crystal-derived fibers using the molten core method (MCM), effectively bypassing the solubility constraints of conventional vapor deposition. This approach significantly extended the fluorescence lifetime of Tm³⁺ to 63 μ s, enhancing the potential for energy conversion within the 2 μ m band.

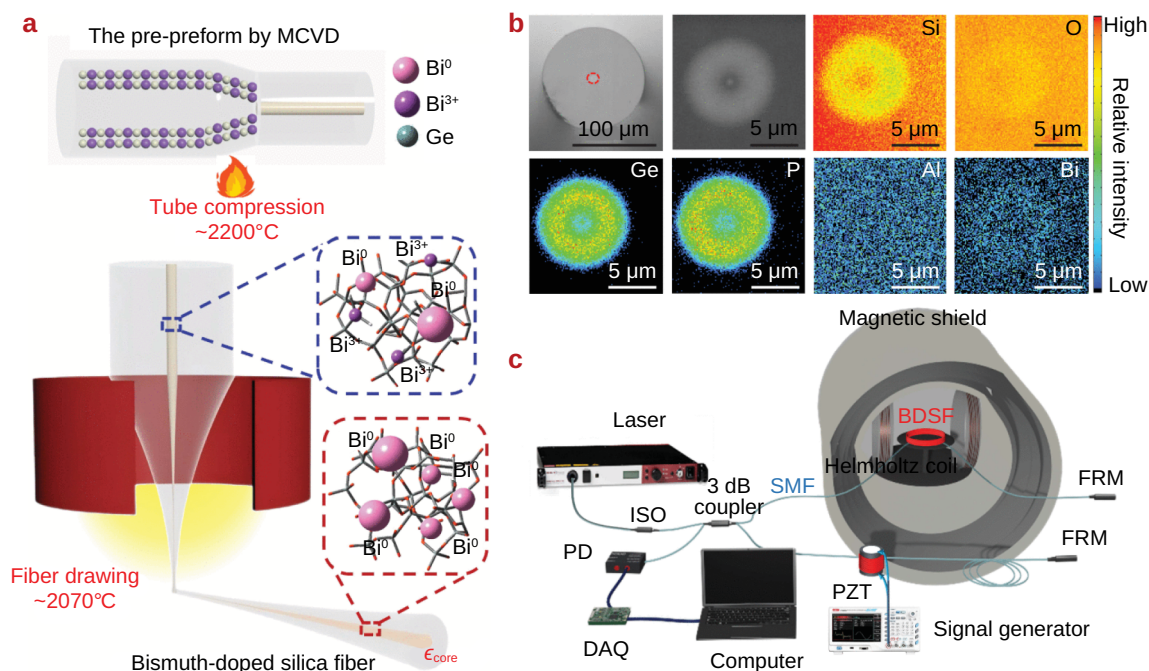


Fig. 2 | (a) Schematic of the valency reduction process in a high-temperature reducing atmosphere during optical fiber fabrication. (b) The electron-probe microanalyzer images of the representative Si, O, Ge, P, Al, and Bi. (c) Magnetorefractive measurement system based on fiber-optic Michelson interferometric. ISO: isolator. PD: photoelectric detector. DAQ: data acquisition card. PZT: piezoelectric transducer. FRM: Faraday rotator mirror. SMF: single-mode fiber. Figure reproduced with permission from (a–c) ref.³⁴, IEEE Xplore.

As fiber sensing networks are deployed in increasingly diverse operating environments, improving the environmental robustness of active fibers at the fabrication level has become a central design target. To optimize the reliability of sensing networks in extreme environments, researchers have investigated both shielding mechanisms and kinetic stability. For instance, Wen et al.⁴⁰ introduced bismuth—an element with a large atomic mass—into the cladding of EDFs. By leveraging the shielding effect against incident ionizing particles and the multi-valence state energy absorption characteristics of bismuth, they reduced the radiation-induced gain variation by 31.9%, thereby enhancing the gain stability of the fiber under extreme radiation fields. Furthermore, Luo et al.⁴¹ established a first-order kinetic model to reveal the interaction effect of bismuth nanoparticles on luminescent active centers, providing a basis for optimizing the fluorescence kinetic stability of active fibers in complex environments. To address extreme scenarios such as cryogenic environments, researchers have also explored novel matrix fabrication and the regulation mechanisms of low-temperature physical properties. By investigating the temperature-dependent fluorescence of ytterbium-doped borophosphosilicate fibers below room temperature (experimentally to 238 K, with the cooling response further modeled into the cryogenic regime), Topper et al.⁴² showed that the smaller Stark-level splitting of the borophosphosilicate host allows higher-lying Yb³⁺ sublevels to remain thermally populated at much lower temperatures than those in aluminosilicate hosts. This

population distribution sustains red-tail resonant absorption, a prerequisite for anti-Stokes fluorescence cooling, but the faster red-shift of the mean fluorescence wavelength also indicates that low parasitic background absorption and high external quantum efficiency remain critical design constraints. Therefore, the significance of this work lies not only in identifying a cryogenic-compatible host matrix but also in linking glass composition, energy-level occupancy, and heat-management efficiency, which provides a mechanistic basis for designing active fibers with improved low-temperature luminescence stability. Together, these advances improve the energy-conversion and spectral characteristics of active fibers, supporting their use in more robust sensing components.

In summary, the development of single-doped active fibers primarily focuses on overcoming the intrinsic limitations of host materials regarding rare-earth ion solubility and non-radiative transitions. By introducing high-precision deposition processes such as ALD and the MCM, researchers have effectively suppressed concentration quenching caused by ion clustering^{34–36}. This progress has expanded gain capabilities in specific spectral bands, including the visible and mid-infrared regions. From a network perspective, these advances define the energy and stability baseline of active sensing units by determining the accessible spectral windows, pump efficiency, and environmental tolerance. However, constrained by the fixed energy-level structures of individual rare-earth ions, single-doped

systems still face fundamental physical limitations in further expanding absorption cross-sections and emission bandwidths. To meet the demand of sensing networks for broadband signal sources⁴³ with high pump absorption efficiency, multi-doped systems have become an important approach for enhancing energy conversion in optical fibers.

2.1.2 Co-doped fibers: energy transfer and microscopic regulation

By incorporating multiple active ions or functional co-dopants into the host matrix, multi-doped fibers leverage inter-ionic energy transfer, coordination field modulation, and matrix defect regulation. These mechanisms can mitigate several limitations of single-doped systems regarding gain bandwidth, pump absorption efficiency, and environmental adaptability. In sensing networks, the development of multi-doped systems primarily follows three directions. First, sensitizer ions such as Yb^{3+} increase pump absorption in the gain fiber and support high-power output within a compact active length for loss compensation⁴⁴. Second, semiconductor or multicomponent co-doping can reshape the local field around active species and strengthen broadband sensitization, leading to broadband luminescence or gain enhancement over a wider spectral range⁴⁵. Third, defect-state regulation in co-doped fibers modifies the behavior of active centers and controls luminescence kinetics, which is essential for maintaining stable emission in complex environments⁴⁶. Recent work has therefore moved from the macroscopic evaluation of energy-transfer efficiency toward microscopic control over active-center dynamics. Studies have also begun to clarify how external fields, including radiation and temperature, modulate the performance of multicomponent active media.

To meet the requirements of sensing networks for broadband gain and high conversion efficiency, recent studies have used multi-ion synergy to regulate active-center formation, energy transfer, and emission processes. These efforts mainly involve constructing target-band active centers, improving rare-earth emission efficiency, and broadening emission bandwidth through multi-ion coupling. For instance, to address the demand for O-band gain, Wang et al.⁴⁷ fabricated Bi/P co-doped silica fibers (BPDFs) using ALD technology. By constructing specific local structures through the introduction of a phosphosilicate matrix, they achieved 20 dB gain within the 1298–1348 nm range. In Er-containing systems, multi-ion and matrix regulation are often used to improve Er^{3+} emission efficiency. For Er/Yb co-doped fibers (EYDFs), Li et al.⁴⁸ showed that the ASE flatness in the C+L band could be regulated by tailoring the Er^{3+} doping concentration. They used a single-mode EYDF with a fiber-core absorption of 41 dB/m at 1535 nm to achieve flattened gain over 1540–1615 nm. Based on this fiber, they further demonstrated an EYDF amplifier with a tunable gain wavelength and an output power exceeding 100 W. Wen et al.⁴⁹ found that the introduction of Bi ions

extended the fluorescence lifetime of Er^{3+} at 1535 nm by 0.68 ms, significantly enhancing the emission efficiency. From the perspective of host-matrix optimization, Ravi et al.⁵⁰ synergistically modified the bismuth borate matrix with Gd_2O_3 , K_2O , and Li_2O . The heavy-metal components reduced phonon energy and thereby inhibited Er^{3+} fluorescence quenching, even at concentrations as high as 3.0 mol%. Wang et al.⁵¹ fabricated PbS/Er co-doped fibers (PEDFs) utilizing ALD combined with MCVD technology. They confirmed that the introduction of PbS modified the local environment of Er^{3+} and enhanced NIR sensitization efficiency. Under 1310 nm pumping via a two-photon absorption mechanism, L+-band amplification covering up to 1627 nm was achieved with a gain exceeding 20 dB. Beyond Er-based emission enhancement, multi-ion coupling has also been used to broaden the emission band. Miluski et al.⁵² fabricated Tm/Ho co-doped fibers using MCVD chelate doping technology. By precisely regulating the concentration ratio and spatial distribution of the two ions, they achieved an ultra-broadband emission with a full width at half maximum (FWHM) of 318 nm. Together, these studies show a coherent design route: multi-ion co-doping can regulate active-center formation, local emission environments, and sensitization pathways, thereby improving gain efficiency and extending the operating bandwidth.

A second line of work has examined the physical responses of multi-component systems in extreme environments, with emphasis on luminescence kinetics and damage recovery. In these studies, the key issue is not only whether irradiation degrades fiber performance, but also how radiation-induced defects, trap states, and active centers regulate optical loss, emission efficiency, and recovery behavior. For instance, Luo et al.⁵³ investigated the effects of gamma-ray, electron-beam, and mixed neutron/gamma irradiation on EYDFs, focusing on radiation-induced attenuation (RIA), unsaturable loss at 830 nm, emission behavior, and fluorescence lifetime. The results showed that irradiation increased RIA and the 830 nm unsaturable loss, while reducing emission intensity and slope efficiency. The authors attributed the emission degradation to the combined effects of RIA and fluorescence-lifetime shortening, with RIA identified as the dominant contributor. Gamma-ray and electron-beam irradiation showed broadly comparable effects on RIA and emission reduction, whereas mixed neutron/gamma irradiation exhibited a different attenuation response, possibly related to neutron-induced bleaching or conversion of radiation-induced defects (Fig. 3(a, b)). This naturally leads to studies on whether irradiation-induced optical losses can be recovered after exposure. Hou et al.⁵⁴ investigated the photo-bleaching (PB) effect of various laser wavelengths on previously irradiated EYDFs, finding that 532 nm laser light offers the optimal recovery effect for phosphorus-related color center defects. This indicates that the radiation response of EYDFs can be partially mitigated by reducing specific radiation-induced color-center absorption, linking

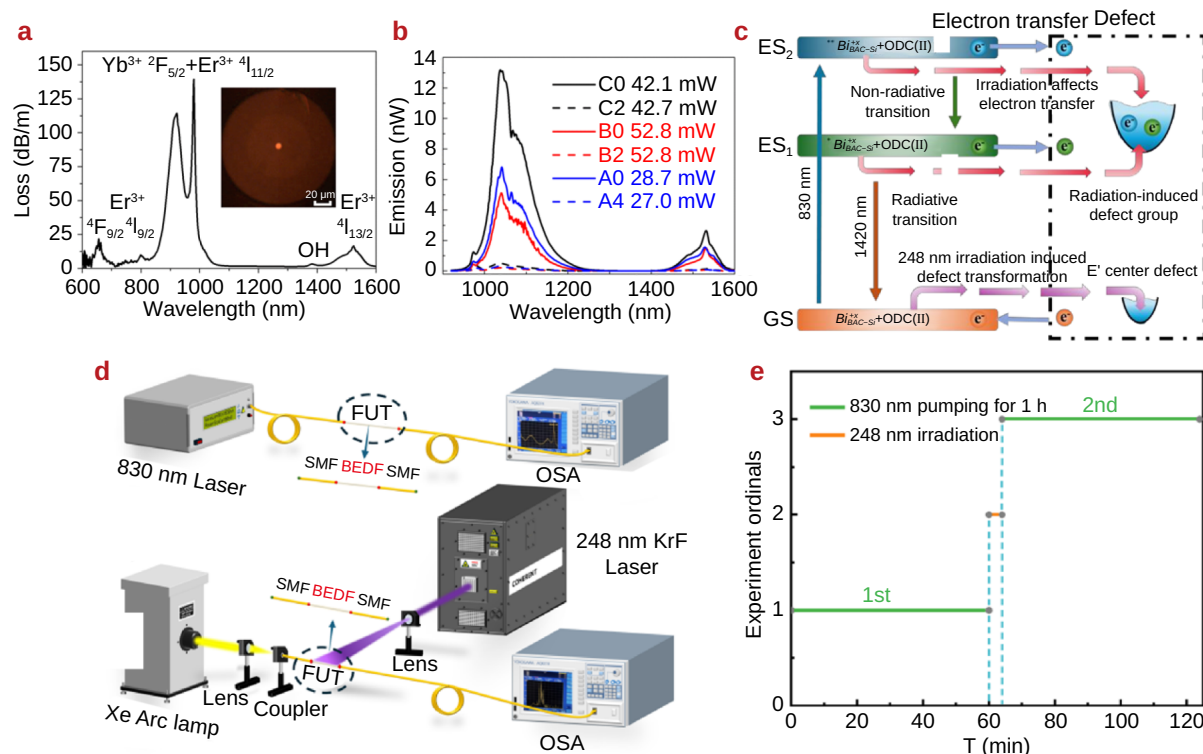


Fig. 3 | Broadband emission regulation of active fibers based on advanced doping processes and multi-element synergy. (a) Attenuation spectrum of the EYDF sample used. The inset is the microscope image of the EYDF cross section. (b) Emission spectra of non-irradiated and irradiated EYDF samples exposed to different types of ionizing radiation. (c) PB mechanism of BAC-Si under 830 nm pumping and 248 nm irradiation. (d) Experimental setup for emission and loss measurements. (e) A schematic diagram of the experimental procedure. Figure reproduced with permission from (a, b) ref.⁵³, IEEE Xplore. (c–e) ref.⁵⁵, Optica Publishing Group.

irradiation-induced degradation with post-irradiation optical recovery. In Bi/Er co-doped fibers (BEDFs), Chu et al.⁵⁵ further examined the PB of silica-related bismuth active centers (BAC-Si) using a sequential protocol of 830 nm pumping, 248 nm UV irradiation and 830 nm re-pumping. They showed that UV-induced changes in BAC-Si reduced its luminescence intensity and enhanced the subsequent PB process, clarifying how defect transformation affects BAC-Si luminescence stability and PB behavior (Fig. 3(c–e)). Unlike the EYDF studies that emphasize irradiation-induced loss and recovery, this work highlights how UV-induced defect transformation governs the PB stability of BAC-Si. In contrast to irradiation-induced degradation and optical recovery, Dong et al.⁵⁶ discovered that gamma radiation significantly enhances the luminescence intensity of aluminum-related lead active centers (PAC-Al) in PbS/Al co-doped fibers. Specifically, a fluorescence enhancement of over 16 dB was achieved at a dose of 0.5 kGy, demonstrating the potential for adaptive gain compensation in radiation environments. This result further shows that radiation does not always act only as a degradation source; under suitable dopant–matrix configurations, it can also activate or strengthen specific luminescent centers. Beyond gain-related luminescence modulation, radiation-induced emission has

also been explored for dosimetry. Fricano et al.⁵⁷ investigated the radioluminescence (RIL) characteristics of Ce/Tb co-doped sol-gel fibers under proton irradiation, confirming that pre-irradiation treatment significantly improves the linearity of online dose monitoring by filling deep trap sites. Thus, defect and trap-state engineering can serve both active-fiber performance stabilization and radiation-sensing functions. Collectively, these advances show that dopant interactions and matrix-defect regulation can tailor energy flow, luminescence recovery, and radiation response in multi-doped active fibers. They therefore provide a materials basis for improving environmental stability, radiation response, and functional reliability in sensing networks.

Multi-doped systems can alleviate some energy-level constraints of single-ion emission through inter-ionic energy transfer and local coordination-field modification. By coupling ionic energy levels and regulating host defect states, researchers have expanded spectral coverage and elucidated the response mechanisms of active centers under external fields (e.g., light, heat, and ionizing radiation)^{24,58,59}. Consequently, these advancements enhance the stability of fluorescence dynamics in complex environments. By improving gain stability and emission efficiency, such material-level optimization can help mitigate SNR degradation in

long-range sensing networks. Thus, co-doping expands active fibers beyond single-ion gain media by enabling controlled energy transfer, broader emission and more stable responses to external perturbations. These functional benefits must, however, be balanced against material-level trade-offs. Higher dopant concentrations and stronger energy transfer can shorten the required active length and improve pump utilization. However, they can also increase ion clustering, concentration quenching and defect-related instability. The preferred co-doped design is therefore not necessarily the one with the highest isolated gain. Instead, it is the design that provides the required spectral range, pump efficiency and environmental stability under the intended operating conditions.

2.1.3 Network-oriented applications: sources, amplifiers and sensors

The optimization of active components and the elucidation of energy-transfer mechanisms have driven advances rare-earth-doped active fibers in high-performance light sources, broadband optical amplification and precision sensing. This section reviews recent advancements across three primary categories: fiber laser sources, optical fiber amplifiers, and optical fiber sensors.

Within the domain of fiber laser sources, current research focuses on wavelength tunability, stable wavelength switching, dynamic spectral control, and operational stability. For example, Sun et al.⁶⁰ constructed a ring-cavity laser utilizing Er:YAG nanocrystalline composite fibers. This system achieved a continuously tunable, ultra-broadband output spanning 126 nm across the S, C, and L bands (1494–1620 nm), maintaining an optical SNR of ~ 70 dB. For discrete wavelength operation, Yan et al.⁶¹ developed a linear-cavity laser using thulium-doped fiber (TDF), achieving dual-wavelength switching between 1940.62 nm and 2048.18 nm. Extending wavelength switching from dual- to multi-wavelength operation, Yan et al.⁶² introduced polarization loss control into a thulium-holmium co-doped fiber (THDF) laser. This design achieved stable four-wavelength switching in the 1.94 μm band, with linewidths narrower than 2 kHz for each wavelength (Fig. 4(a)). To move from wavelength selection toward dynamic spectral control, Meng et al.⁶³ theoretically demonstrated the tunability of an EDF-based Fabry-Pérot (F-P) resonator via incorporating dynamic Bragg gratings, aimed at optical frequency comb generation and dynamic filtering. Operational stability has also been considered, as Panitzek et al.⁶⁴ tested an EYDF laser system and confirmed that its slope efficiency remained constant during temperature cycling from 0 °C to 60 °C. These studies indicate that active-fiber lasers can provide a source-level basis for wavelength-selectable, low-noise interrogation in fiber sensing networks, while dynamic filtering and thermal-stability control help maintain calibration under environmental drift.

In the field of optical amplifiers, research emphasizes effective loss compensation in communication bands and the extension of gain boundaries. Puttnam et al.⁶⁵ applied a germano-silicate bismuth-doped fiber (G-BDF) amplifier in a large-scale transmission experiment. This study achieved a total data rate of 321 Tb/s over a 50 km fiber link, confirming the practical communication capability of the G-BDF amplifier as part of a broader E/S/C/L-band transmission system spanning 1410.8–1623.1 nm. For gain performance, Wang et al.⁶⁶ used a BDSF in a dual-pump configuration to achieve a flat gain exceeding 23 dB across the 1315–1483 nm range (Fig. 4(b)). Similarly, they utilized a BPDF to achieve a gain greater than 20 dB in the O-band, with a gain coefficient approaching 0.5 dB/m⁴⁷. This high unit-length gain was enabled by P-induced formation of Bi-P active centers, which strengthened O-band excitation compared with Bi-only doping. This indicates that P co-doping is an effective strategy for enhancing O-band gain in Bi-doped fibers. Beyond O-, E-, and S-band gain enhancement, long-wavelength spectral extension has also been pursued. Jia et al.⁶⁷ introduced a terbium-doped cladding into a thulium-doped fluorotellurite glass fiber. Their design used cooperative ion absorption to suppress short-wavelength emission, enabling spectral control over the 1600–1680 nm range. Although demonstrated largely in communication-oriented systems, these amplifier advances are also relevant to sensing networks because they provide loss compensation and band extension, allowing weak return signals from remote or multiplexed sensing units to remain measurable even over longer links.

In the field of sensing, active fibers can function as sensing media, radiation-responsive materials, or signal-enhancement components, enabling high-sensitivity detection in different scenarios. Fu et al.^{68,69} developed a cascaded interferometer and a ring-cavity laser sensing system using EYDFs. In the cascaded MZI, the EYDF acts as both the broadband ASE source and the sensing segment, so temperature/curvature demodulation is strengthened by combining dopant emission with modal interference. These active fiber sensing designs enabled highly sensitive temperature sensing and wideband (1–48 kHz) vibration recognition (Fig. 4(c)). Radiation-induced modification offers another route to enhance fiber-sensor response. Luo et al.⁷⁰ confirmed that modifying the core refractive index through 50 kGy of high-dose radiation can enhance the temperature sensitivity of BEDF sensors by 50%. When radiation is the measurand, Fricano et al.^{57,71} advanced Ce-based sol-gel fiber dosimetry from simple RIL readout toward controllable, microscale dose monitoring. Under proton irradiation (approximately 27–63 MeV), X-ray pre-irradiation up to 250 kGy improved the RIL response by progressively filling deep trap states and reducing the bright-burn effect, thereby enhancing dose-response linearity. In tapered Ce-doped fibers, reducing the doped core diameter from 25 to 4.2 μm increased the volume-normalized radiation sensitivity while

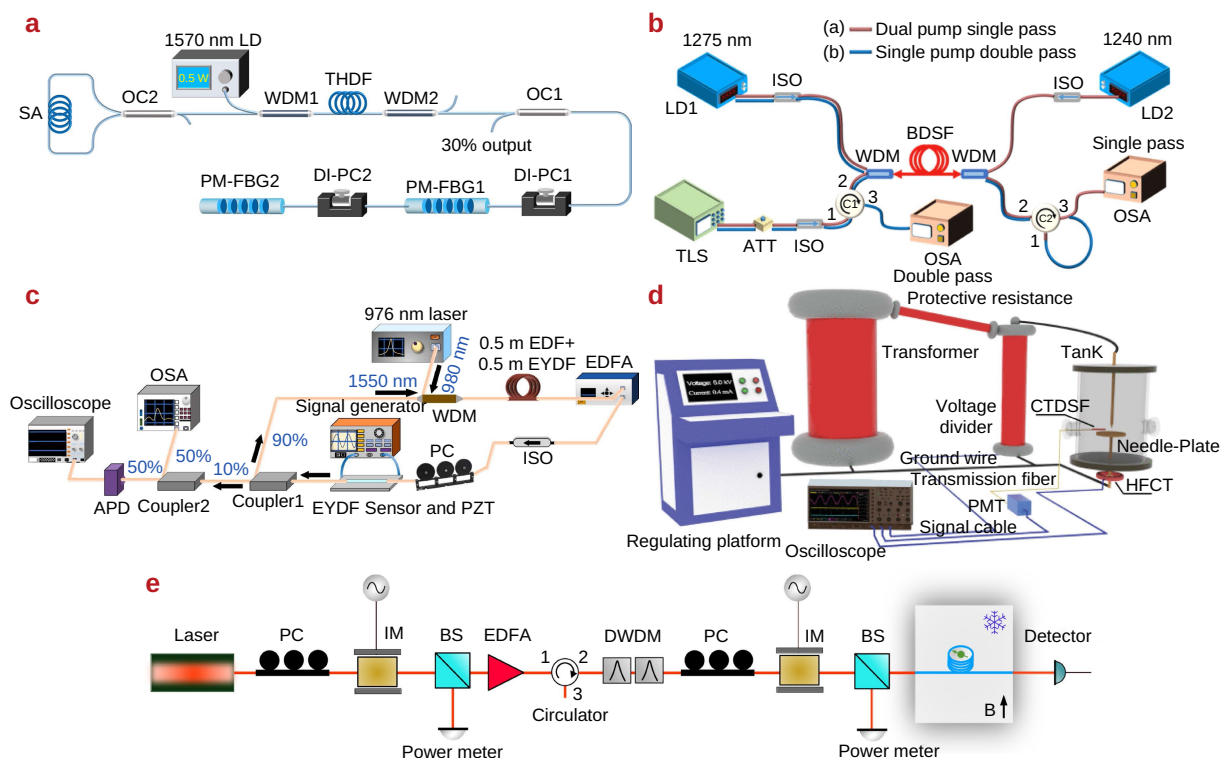


Fig. 4 | (a) Schematic diagram of the proposed four-wavelength switchable single-longitudinal-mode (SLM) narrow-linewidth THDF laser. LD: Laser diode, WDM: Wavelength division multiplexer, OC: Optical coupler, DI-PC: Drop-in polarization controller, PM-FBG: Polarization-maintaining fiber Bragg grating, SA: Saturable absorber. (b) Experimental set-up of the 1275+1240 nm dual-pump single-pass and 1275 nm single-pump double-pass of Bi-doped fiber amplifier. (c) Experimental system for measuring different vibration frequencies and driving voltages. (d) Experimental setup utilizing the Ce and Tb co-doped silica fiber sensor for Partial discharge detection. (e) Schematic of the experimental setup for photon-echo measurements in EDF. A continuous-wave diode laser at 1532.5 nm is pulsed using an intensity modulator (IM), with polarization controlled by a polarization controller (PC). The output is monitored by a beam splitter (BS) and a power meter. The light is amplified by an EDF amplifier (EDFA), with a circulator preventing back reflections. Dense wavelength-division multiplexing (DWDM) filters suppress ASE before the light enters the EDF housed in a dilution refrigerator. The photon-echo signal is detected by a fast photodetector. Figure reproduced with permission from (a) ref.⁶², IEEE Xplore. (b) ref.⁶⁶, IEEE Xplore. (c) ref.⁶⁹, Elsevier B.V. (d) ref.⁷², IEEE Xplore. (e) ref.⁷⁴, Optica Publishing Group.

preserving dose-rate monitoring over 0.5–170 mGy(SiO₂)/s. These results indicate that defect-state conditioning can improve response linearity and stability, while taper-based microgeometry engineering reduces the sensitive volume and supports microscale dose monitoring with improved spatial localization. Beyond radiation dosimetry, dopant-mediated spectral conversion can also translate weak ultraviolet signals into fiber-transmittable optical responses. Wang et al.⁷² utilized a Ce/Tb co-doped silica fiber (CTDSF) to capture partial-discharge signals in power facilities, achieving a response sensitivity of 0.22 ns·V/pC (Fig. 4(d)). Mechanistically, Ce³⁺ absorbs light at ~302 nm, which overlaps well with the ultraviolet emission band of partial discharges, and transfers energy to Tb³⁺, which emits strongly at 542 nm. This spectral conversion turns weak ultraviolet discharge events into fiber-transmittable visible signals. This CTDSF sensor showed approximately 2.4-fold higher sensitivity compared with plastic scintillation fibers, highlighting the value of rare-earth energy-transfer design

for remote all-fiber monitoring in high-voltage equipment. Active fibers can also improve sensing performance indirectly by amplifying the interrogation light. Wang et al.⁷³ employed photoacoustic spectroscopy (PAS) enhanced by a TDF amplifier to improve the detection limit of carbon dioxide to 190 ppb. In this PAS system, in-band pumping of the TDF amplifies the 2004 nm distributed feedback laser power, thereby strengthening photoacoustic excitation and improving gas-detection sensitivity. Finally, from the perspective of fundamental physical limits, Rasekh et al.⁷⁴ measured an effective homogeneous linewidth of approximately 8 kHz in EDFs at ~7 mK and 0.09 T, representing an improvement of about two orders of magnitude compared with previous measurements near 700 mK (Fig. 4(e)). This finding demonstrates that EDFs can maintain long optical coherence under millikelvin conditions, supporting their potential use in fiber-based quantum storage and possibly other cryogenic coherent-photon applications.

Viewed at the network level, the preceding source,

amplifier and sensor studies should be compared by the functions they support rather than a single headline metric. Broad tuning and wavelength switching increase interrogation flexibility, but they can add cavity and control complexity. High output power extends the available link margin, whereas low-noise and narrow-linewidth operation is more important for phase- or wavelength-resolved sensing. For amplifiers, gain magnitude must be considered together with gain flatness, noise, saturation characteristics, pump efficiency and modal uniformity. A high peak gain is not automatically preferable if it reduces dynamic range, increases amplified spontaneous emission or produces unequal responses among multiplexed channels. The appropriate architecture therefore depends on whether the dominant network constraint lies in node density, spectral coverage, spatial-mode capacity or calibration stability.

In summary, active fibers fabricated via traditional vapor deposition have established a foundational role in long-haul in-line amplification and high-quality lasing, owing to their extremely low background loss and high axial consistency. These examples^{47,62,66,69,72} show that composition-engineered active fibers can provide basic active functions, including gain, lasing and signal conversion. However, their nearly cylindrical symmetry and relatively simple step-index profiles impose constraints, limiting the degrees of freedom for optical field manipulation. Specifically, conventional step-index cylindrical waveguides face inherent physical limitations, including modal gain mismatch in higher-order modes and power-scaling bottlenecks caused by low nonlinear thresholds. Furthermore, this symmetry hinders the independent control of polarization states and OAM, while restricting the advanced utilization of evanescent field interactions. These requirements shift the design emphasis from material-level doping optimization toward spatial waveguide engineering, making microstructured active fibers a promising route for multiparameter decoupling, spatial-mode operation and structured-light generation in complex sensing networks.

2.2 Microstructured active fibers: waveguide engineering and light-field control

Microstructured active fibers address the limitations of composition-only design by introducing geometric features, such as air-hole arrays, heterogeneous refractive-index profiles, or complex doping distributions, into the waveguide structure⁷⁵. These geometric degrees of freedom facilitate a strategic shift from chemical composition adjustment to spatial waveguide engineering²¹. Microstructures manipulate optical-field evolution by introducing geometric degrees of freedom into the waveguide. By reconstructing mode distributions, refractive index profiles, and the spatial distribution of rare-earth elements, this approach can relax some limitations of uniform fibers in modal, polarization and field-distribution control. This structural dimensional-

ity grants optical fibers significant flexibility in spectral tailoring, mode manipulation, and light transmission control. Furthermore, it provides a useful waveguide platform for optical information transmission and multiparameter sensing.

2.2.1 Structural design: mode regulation and gain equalization

In recent years, various microstructured active fibers have been developed, including photonic crystal structures⁷⁶, ring-core structures⁷⁷, multi-core structures⁷⁸, graded-index profiles⁷⁹ and suspended-core designs⁸⁰. These developments have played a vital role in optical fiber communication and sensing. In particular, photonic crystal fibers (PCFs) offer a flexible microstructured platform for tailoring mode area, polarization behavior, and high-order-mode gain through air-hole geometry. In designing a large-mode-area PCF, Feng et al.⁷⁶ utilized a Yb/Al/P/F quaternary co-doping scheme. By leveraging the ability of fluorine (F) to lower the host refractive index, they effectively compensated for the index increase typically caused by Yb/Al co-doping. This approach achieved an extremely low numerical aperture (NA) through the integration of material and microstructure, ensuring single-mode operation even with a large mode area (Fig. 5(a, b)). The role of PCF geometry can also extend from mode-area scaling to polarization control. Luo et al.⁸¹ developed a birefringent bismuth/erbium co-doped photonic crystal fiber using an asymmetric air-hole array. By utilizing the stress birefringence generated by geometric anisotropy, they broke the polarization degeneracy of active-center emission, achieving efficient polarized emission in the NIR band. For high-order-mode operation, Rehan et al.⁸² proposed an erbium-doped circular photonic crystal fiber. By combining multi-sized, cyclically arranged air holes with an annular erbium-doped region, they aligned the spatial distribution of the gain medium with the high-intensity regions of 20 OAM modes. This design provides a structural basis for high-order-mode amplification.

Driven by the demand for increased capacity in optical networks, researchers have constructed spatially tailored fiber doping profiles to regulate mode overlap integrals, thereby addressing the differential modal gain (DMG) issue in space-division multiplexing (SDM). For example, Chen et al.⁷⁷ developed an EDF with a double-layer ring-core structure. By distributing Er³⁺ ions within two annular regions of specific widths and spacings, this design structurally compensates for the radial distribution differences among various mode orders. Such design logic was later used by the same group to support cylindrical vector beam generation. Chen et al.⁸³ developed a ring-core ytterbium-doped fiber. By precisely tailoring the doping concentration distribution and the refractive index profile, they achieved an efficient match between the fiber gain characteristics and cylindrical vector modes, enabling stable cylindrical vector beam output at 1064 nm. Beyond gain equalization for

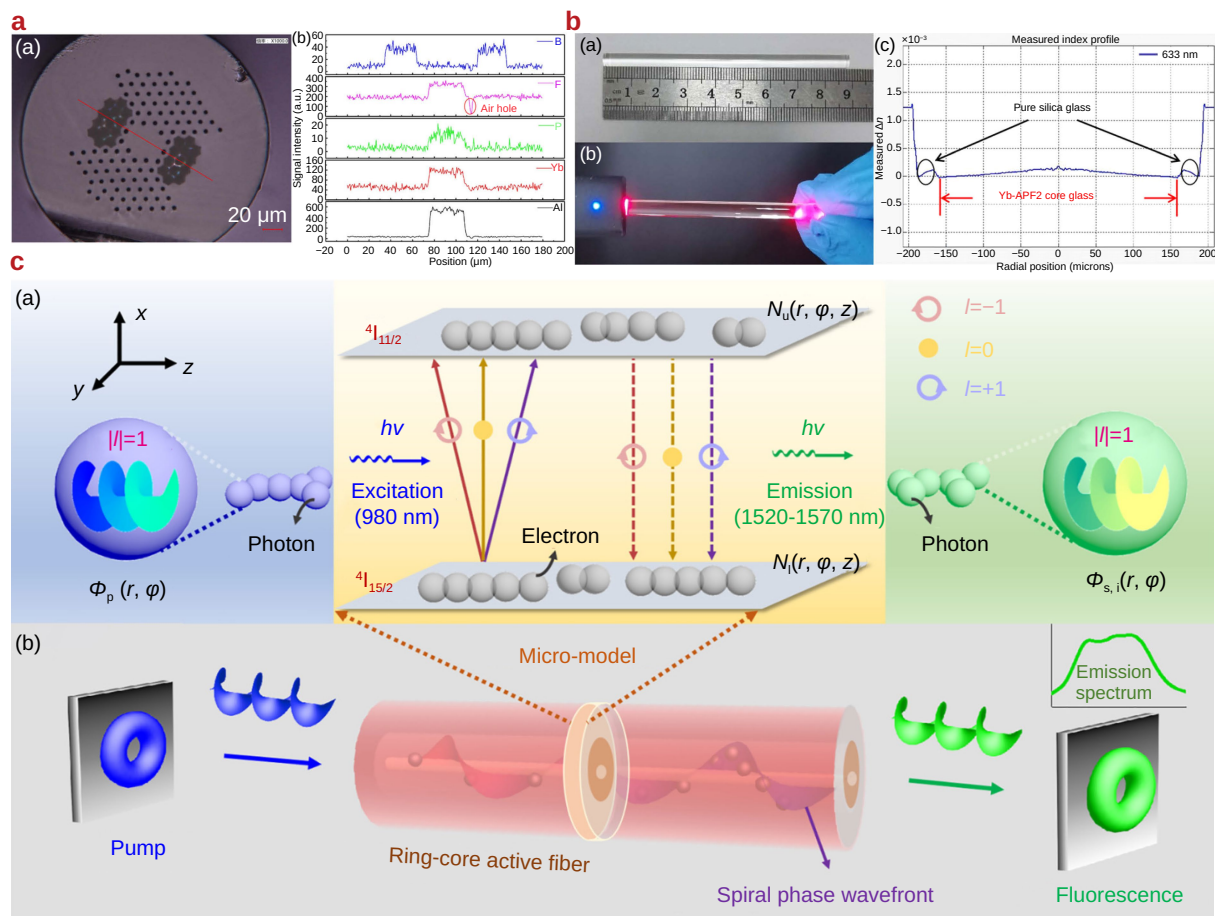


Fig. 5 | (a) Microscope image of the fabricated polarization maintaining PCF and radial elemental profiles obtained by electron-probe micro-analysis. (b) Core glass rod sized 5 mm × 90 mm and Pictures of glass rod illuminated by a red laser pointer. (c) OAM fluorescence emission process in a ring-core active optical fiber. Figure reproduced with permission from (a, b) ref.⁷⁶, IEEE Xplore. (c) ref.⁸⁶, WILEY.

SDM, annular or nested dopant distributions can also be used to manage spectral competition and ASE. Ye et al.⁸⁴ designed a TDF featuring a nested annular-doped core. By reducing the overlap between the mode and the doped region, they utilized a spatial filtering effect to suppress ASE competition in the long-wavelength band. This design achieved hundred-watt-level laser output at 1908 nm while simultaneously enhancing thermal management performance. For few-mode amplification, the same idea can be applied more directly by controlling the overlap between the guided modes and the doped region. Pei et al.⁸⁵ employed a three-layer erbium-ion stepped-doping structure in conjunction with a double-clad micro-waveguide. This configuration achieved precise spatial matching between six spatial modes and the gain medium distribution, significantly reducing intermodal gain variation. These studies indicate that radial dopant engineering is not simply a means of increasing rare-earth loading, but a structural approach for redistributing gain among different spatial or spectral channels. The same principle can also be extended beyond gain equalization, where tailored active-fiber struc-

tures are used to regulate broadband rare-earth emission profiles or generate structured light. Miluski et al.⁵² fabricated a double-clad $\text{Tm}^{3+}/\text{Ho}^{3+}$ co-doped fiber with a multi-ring profiled core using MCVD chelate doping technology. In their design, the radial distribution of the two rare-earth ions is not merely a fabrication detail, but a way to tune the spatial overlap among the guided mode, the doped regions, and the Tm-to-Ho energy-transfer pathway. As the fiber length increased, the Ho^{3+} emission at around 2.0–2.1 μm became stronger, while the overall eye-safe emission covered 1.6–2.1 μm with an FWHM of 318 nm for a 2 m fiber and 270 nm for a 10 m fiber, respectively. This work illustrates how annular dopant profiling can shape broadband gain in large-mode-area fibers while retaining weakly guiding operation ($NA = 0.054$, mode field diameter = 42.2 μm at 2000 nm). In a different but related direction, ring-core active fibers have also been used to generate structured light directly from rare-earth emission. Wen et al.⁸⁶ further extended microstructured active fibers from modal gain management to structured-light generation by using a ring-core EDF as an active vortex-field medium. Their photon-

electron interaction model and experiments showed that broadband Er^{3+} fluorescence can be emitted and transmitted with OAM characteristics, forming donut-shaped beams with spiral-phase wavefronts over a spectral width of up to 50 nm. By extracting narrow bands at 1529.6, 1543.3, 1553.0, and 1561.4 nm and verifying spiral interferograms, the study demonstrated that spontaneous rare-earth emission itself can be converted into OAM-bearing light, rather than relying only on passive mode conversion after lasing (Fig. 5(c)). In addition to spatial structuring, host-glass optimization provides another route for improving rare-earth luminescence and overall fiber performance. Tan et al.⁸⁷ prepared Er^{3+} -doped bismuth germanate laser glass and used Raman analyses to relate the glass network topology to NIR luminescence performance. When this glass was evaluated as the gain medium in a multi-core PCF design, the calculated inter-core crosstalk reached -56.8 dB with an effective mode-field area of $363 \mu\text{m}^2$. Together, these studies show that microstructured active fibers are evolving along two coupled axes: spatial engineering of the optical field and dopant distribution, and host-network engineering that stabilizes active ions and improves gain performance. Overall, these studies reflect a shift from simply incorporating rare-earth ions to deliberately coordinating dopant placement, light-matter overlap, and host-glass composition.

The primary advantage of microstructured active fibers lies in their ability to reconfigure the spatial overlap integral between the optical field and the gain medium through geometric design⁸⁸. This capability helps address limitations of traditional step-index fibers in optical-field control and mode-gain equalization. This shift from materials-only optimization toward structural design can help reduce mode crosstalk and DMG in selected spatial-mode systems, including those based on OAM or vector modes⁸⁹. Ultimately, these structural improvements provide a physical basis for developing sensitive sensing architectures and active relay components in complex optical networks. In this sense, microstructured active fibers convert spatial geometry into an additional design variable for gain and emission control: they define where gain is delivered, which modes are favored, and how structured optical fields are generated. In this context, OAM and vector modes should be viewed as representative cases of structured-light generation enabled by active waveguide engineering, rather than as the sole focus of specialty active fibers. Realizing these benefits, however, requires greater fabrication precision and increases system-integration complexity. Ring-core and multilayer doping profiles can reduce DMG and support structured modes, but their performance is particularly sensitive to geometrical deviations, splicing mismatches and modal-coupling errors. Their advantages at network level are therefore greatest when improved channel balance or reduced crosstalk justifies the additional fabrication and coupling complexity.

2.2.2 Applications: SDM and multiparameter sensing

At the application level, microstructured active fibers are useful because asymmetric or periodic topologies can tailor waveguide boundary conditions. This enables control over modal evolution, phase distribution, and intermodal coupling. This structural tailoring can mitigate some constraints of traditional step-index fibers in modal gain equalization and power handling, while also enhancing evanescent-field interactions. Consequently, this architecture facilitates highly sensitive responses and selective sensing of external parameters. Through advanced geometric engineering, microstructured active fibers can combine gain, waveguide modulation and sensing functions in selected device architectures.

In laser and mode-control applications, active fibers with specialized microstructures can provide intra-cavity filtering, phase manipulation, or spatial-mode discrimination, thereby supporting laser tuning and complex-mode regulation. Regarding light source switching and tuning, Perezcampos-Mayoral et al.⁹⁰ constructed a miniature MZI using a thin-core EDF. By leveraging the high sensitivity of the thin-core structure to bending curvature, they achieved flexible switching of multi-wavelength outputs in erbium-doped lasers (Fig. 6(a, b)). This result demonstrates how specialized core geometries can function as intra-cavity filters rather than only serving as passive transmission media. In the field of vector laser generation, Wen et al.⁹¹ utilized a spirally twisted, high-concentration erbium-doped few-mode fiber. By leveraging the geometric phase conversion mechanism introduced by physical twisting, they achieved a stable vortex laser output of 22.5 mW in the 1.5 μm band. Unlike the twist-induced phase-control strategy, Firstov et al.⁹² utilized the supermode selection effect of microstructures within a multi-core bismuth-doped fiber to achieve stable lasing in the E-band (1430–1460 nm) (Fig. 6(c, d)). This approach effectively helped reduce the high lasing threshold associated with low-gain ions.

In SDM communication systems, microstructured active fibers are mainly developed to provide simultaneous amplification of multiple spatial channels while controlling DMG. Regarding OAM mode amplification, Rastogi et al.⁹³ utilized a double-clad erbium-doped photonic crystal fiber. By leveraging the strong waveguide confinement generated by the micro-hole array and an ultra-large effective mode area ($>230 \mu\text{m}^2$), they achieved simultaneous amplification of 38 OAM modes with a low nonlinear penalty. To further improve gain uniformity among OAM channels, Gao et al.⁹⁴ employed a center-raised ring-core EDF combined with a multi-layer discrete doping design. The center-raised refractive-index profile improves overlap with five OAM modes while avoiding strong intermodal crosstalk. This configuration achieved parallel amplification of 20 OAM modes across the C-band, with a DMG of less than 0.8 dB. Building on this, Gao et al.⁹⁵ utilized a Gaussian-distribution ring-core structure to further reduce the DMG of four OAM

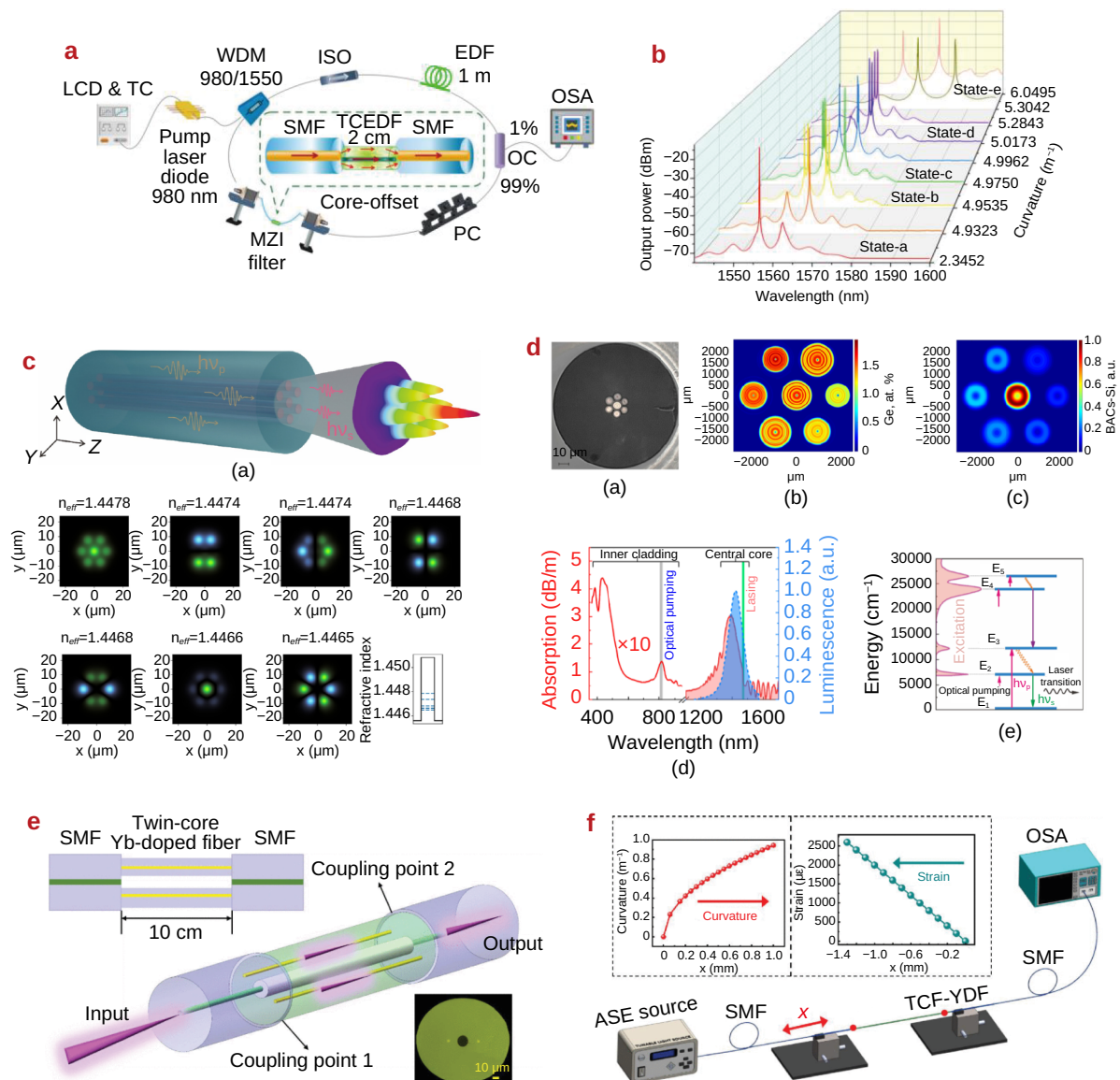


Fig. 6 | (a) Diagram of the multi-wavelength thin-core erbium-doped fiber laser (MTEFL) ring array. (b) MTEFL emission tuning and switching cases generated for single (state-a), quadruple (state-b), triple (state-c), narrow-double (state-d), and double (state-e) lasing signals. (c) A principle scheme of supermode lasing in strongly core-coupled multicore fiber (MCF). (d) The calculated supermodes of the Bi-doped MCF. (e) 3-D schematic of MZI based on SMF-twin-core fiber-SMF structure. The top left corner inset shows plan view, and the bottom right corner inset shows the cross section of twin-core fiber. (f) Schematic of MZI curvature and strain sensing device. Figure reproduced with permission from (a, b) ref.⁹⁰, MDPI. (c, d) ref.⁹², Optica Publishing Group. (e, f) ref.⁹⁸, IEEE Xplore.

mode groups to less than 0.3 dB. Beyond OAM-mode amplification, multi-core active fibers have also been investigated for SDM transmission links and extended gain-band operation. Jaouën et al.⁷⁸ demonstrated a 12-core Er/Yb co-doped microstructured fiber amplifier (MC-EYDFA) for 1200-km long-haul transmission. The MC-EYDFA study further optimized active-fiber length, pump power, and ion concentration to obtain 20 dB C-band gain with 5.3 W pump power in the 12-core architecture. Similarly, Li et al.⁹⁶ developed a 4-core EYDF for the extended L-band. By employing a 1018 nm high-power cladding pumping scheme—combined

with the microstructure's suppression of inter-core cross-gain—they extended the effective gain range to 1575–1625 nm. At the level of photonic-crystal active-fiber design, Xu et al.⁹⁷ utilized the strong waveguide confinement of the air-hole layers for both pump and signal light in an Er/Yb co-doped photonic crystal structure. This significantly enhanced the energy conversion efficiency per unit length, achieving a peak gain as high as 47 dB.

To consolidate the diverse advancements in signal generation and amplification, Table 2 systematically summarizes the key performance metrics of representative active fiber

Table 2 | Performance comparison of active optical fibers in lasers and amplifiers.

Type	Dopant system	Operating wavelength	Key performance metric	Ref.
Laser	Er:YAG nanocrystals	1494–1620 nm	126 nm ultrabroadband continuous tuning, OSNR >70 dB	ref. ⁶⁰
Laser	Tm ³⁺ -doped	1940.62 nm / 2048.18 nm	Flexible dual-wavelength switching	ref. ⁶¹
Laser	Tm ³⁺ -doped	1908 nm	100 W class laser output with effective suppression of spontaneous emission	ref. ⁶⁴
Laser	Er ³⁺ -doped	1.5 μm	Stable 22.5 mW vortex (OAM) lasing output	ref. ⁹¹
Amplifier	Bi-doped	1410.8–1623.1 nm	Supports 50 km link transmission at a total rate of 321 Tb/s	ref. ⁶⁵
Amplifier	Bi-doped	1315–1483 nm	Flat gain >23 dB	ref. ⁶⁶
Amplifier	Er ³⁺ -doped	C band	Parallel amplification of 20 OAM modes, DMG <0.8 dB	ref. ⁹⁴
Amplifier	Er/Yb co-doped	1575–1625 nm	High-power 1018 nm cladding pumping with suppressed inter-core cross-gain	ref. ⁹⁶

lasers and amplifiers. By mapping specific dopant systems to their operating wavelengths, it highlights the representative advances in broadband tunability, mode control and high-gain power scaling. In this system context, Table 2 shows that superior performance is application-dependent. Wide wavelength tuning supports wavelength-multiplexed interrogation, high output power accommodates demanding link budgets, and low differential modal gain preserves channel balance in spatially multiplexed networks. These benefits must be weighed against cavity complexity, pump demand, amplified spontaneous emission, saturation and fabrication tolerance. Active fibers should therefore be selected according to the dominant system constraint rather than to maximized one isolated metric.

Whereas the preceding examples focus mainly on modal control and amplification, multiparameter sensing introduces the additional challenge of separating simultaneous measurand contributions. A single scalar response cannot provide this separation. Multiparameter demodulation therefore requires independent observables, such as shifts in different spectral features, changes in intensity or fluorescence changes, linewidths, modal responses or signals from distinct resonances. After calibration, these responses can be represented by a sensitivity matrix whose elements describe the response of each observable to each measurand. The measurand changes can then be estimated by inversion or fitting, as exemplified by temperature–curvature demodulation in ref.⁶⁸. The condition number describes the sensitivity of this inversion to noise for a stated parameter scaling and matrix norm. A smaller value generally indicates more independent response channels and less noise amplification, whereas a larger value indicates nearly dependent channels and less stable parameter recovery. Cross-sensitivity should be assessed separately by considering responses to non-target measurands and residual errors under simultaneous perturbations. Because the observables, units, parameter scaling and matrix norms vary among the reviewed studies, their condition numbers cannot be compared directly. This framework provides a basis for interpreting the sensing demonstrations below.

Moving from communications to sensing, specialized microstructures can enhance interactions between internal

active components and external physical fields, thereby improving sensitivity and functional integration. Zhao et al.⁹⁸ developed an all-fiber MZI by sandwiching a twin-core ytterbium-doped fiber with a central air hole between two SMFs (Fig. 6(e, f)). The significance of this design lies in coupling two sensing pathways within the same active microstructured fiber: the twin-core geometry produces interference-wavelength shifts for strain, curvature, refractive index, and temperature monitoring, whereas the Yb³⁺ fluorescence response provides an additional channel for high-temperature sensing. These results show that microstructured active fibers can move beyond single-parameter readout by integrating modal-interference demodulation, fluorescence thermometry, and geometry-enhanced field interaction, although cross-sensitivity compensation remains important for practical multiparameter deployment. For mechanical sensing, Correa Serrano et al.⁹⁹ used a three-core EDF in which torsion modulates coupling between linearly arranged cores, achieving a torsion sensitivity of 0.019 nm/°. In addition to geometry-induced modal interference, active microstructures can also combine different rare-earth responses for multi-parameter sensing. Zhou et al.¹⁰⁰ demonstrated a composite sensor based on a hollow-core fiber spliced with EYDF microspheres. By leveraging the distinct thermal responses of these two rare-earth components, they achieved simultaneous sensing of temperature and refractive index. Finally, in radiation monitoring, Fricano et al.⁷¹ applied a tapering process to Ce-doped fibers. By utilizing the tapered micro-waveguide to enhance the capture of RIL signals, they achieved linear monitoring of dose rates ranging from 0.5 to 170 mGy/s.

In summary, microstructured waveguides use asymmetric and periodic topologies to endow active fibers with additional control over optical fields and measurand interactions. These designs enable vector optical-field manipulation and sensitive responses to parameters such as torsion and magnetic fields. They are therefore relevant to fiber light sources, spatial-mode communications and multiparameter sensing. Compared with composition-engineered fibers, microstructured active fibers add field-selective interaction to active gain, allowing a single fiber segment to operate as a

gain medium, modal filter, structured-light generator or multiparameter sensing unit. For multiparameter sensing specifically, reliable decoupling requires independent sensitivities, a well-calibrated sensing matrix and validation under simultaneous perturbations. Microstructural design therefore contributes not only higher sensitivity, but also the independent observables required for stable parameter separation. However, as these devices move toward greater integration and specialization, further progress will require improved manufacturing precision, material compatibility and structural customization. This manufacturing constraint motivates the next route, additive manufacturing, which extends active-fiber design from cross-sectional geometry toward three-dimensional customization¹⁰¹.

2.3 3D-printed active fibers: digital fabrication for customized sensing units

Although microstructured active fibers expand the waveguide design space, most conventionally fabricated structures remain constrained by preform assembly, drilling, stacking and drawing processes. Through digital additive manufacturing, 3D printing is beginning to address the limitations of traditional preform fabrication in producing asymmetric structures, complex multi-core layouts, and spatially controlled material distributions. Digital modeling provides geometric freedom and enables on-demand placement of active components in three dimensions, making additive manufacturing especially relevant for compact and customized next-generation sensing units.

2.3.1 Additive processes and technical bottlenecks

In early work on digitally fabricated active fibers, researchers mainly focused on whether active dopants could be introduced while maintaining acceptable spectroscopic and waveguiding properties. Camacho Rosales et al.¹⁰² utilized direct ink writing (DIW) to extrude a silica nano powder slurry doped with 1 wt% ErCl_3 . Following debinding and high-temperature sintering, the preform was drawn into an EDF. This process achieved an active fiber with an absorption coefficient as high as 151.49 dB/m at 1535 nm, confirming the feasibility of DIW for fabricating high-concentration gain media. To overcome the constraints of fabrication cycles, Maniewski et al.¹⁰³ proposed a rapid prototyping scheme based on laser powder deposition (LPD). Using a CO_2 laser to locally melt doped powders, the transition from raw materials to functional fibers was achieved within a few hours. The resulting Ti-doped core fibers exhibited losses as low as 3.2 dB/m (Fig. 7(a)). Along this laser-based fabrication route, Zhao et al.¹⁰⁴ employed laser additive manufacturing (LAM) to fabricate Nd/Al co-doped silica glass. The measured fluorescence lifetime of Nd^{3+} ions reached 664 μs , suggesting from a spectroscopic perspective that additive manufacturing can help suppress clustering-induced quenching of active ions.

Beyond dopant incorporation, the geometric flexibility of 3D printing has also been exploited to construct more complex active-fiber architectures. Chu et al.¹⁰⁵ used direct light projection (DLP)-based 3D printing to fabricate Bi/Er co-doped silica preforms with single- and seven-core structures, thereby avoiding the time-consuming separation and integration steps required in conventional preform fabrication. The introduction of Bi^{3+} , Er^{3+} , Ge^{4+} , Ti^{4+} , and Al^{3+} further demonstrated the compatibility of additive manufacturing with multi-dopant active glass systems. The resulting BEDFs showed broadband near-infrared luminescence extending across the telecommunications O-L bands (Fig. 7(b, c)). However, the seven-core fibers also showed core asymmetry, shrinkage, and increased loss, indicating that drawing conditions must be carefully optimized as the structural complexity increases. More recently, Wang et al.¹⁰¹ utilized DLP technology to directly print a cladding featuring a highly complex air-hole array. By physically assembling this cladding with an ytterbium-doped core rod via UV curing and sintering, they successfully drew a specialty fiber that integrates microstructures with active properties. Experiments confirmed that the fabricated ytterbium-doped fiber (YDF) maintains stable waveguide characteristics even in high-temperature environments (up to 653 K), demonstrating its potential for structured sensing in extreme conditions. Finally, as additively manufactured active fibers move toward single- and multi-core integration, structural fidelity during fiber drawing becomes a key fabrication issue.

The integration of 3D printing technology has provided a route to overcome the geometric and material-distribution constraints of traditional preform manufacturing, enabling the customized, on-demand design of gain components and waveguide structures¹⁰¹. From the perspective of material evolution mechanisms, the specific in situ curing or localized fusion processes of additive manufacturing allow for the pre-distribution of functional components at the micro- to nanoscale. Combined with a unique non-equilibrium thermal history, these processes may help preserve a high degree of atomic-scale disorder during glass formation. Consequently, this approach provides a new technical pathway for mitigating ion clustering in high-concentration doping and exploring novel non-equilibrium host glasses. However, because photosensitive resin purity and microscopic interfacial defects generated by layer-by-layer stacking remain difficult to control, the background loss of printed fibers is still higher than that of fibers fabricated by conventional processes. This implies that the current evolutionary trajectory of 3D-printed active fibers is unlikely to replace traditional fibers completely, but will instead focus on short-range, highly integrated specialty functional devices¹⁰⁶. Thus, the near-term value of 3D-printed active fibers is not to replace low-loss fibers fabricated by mature vapor-deposition processes, but to create compact, customized, and highly integrated sensing units whose main advantage lies in local functional complexity.

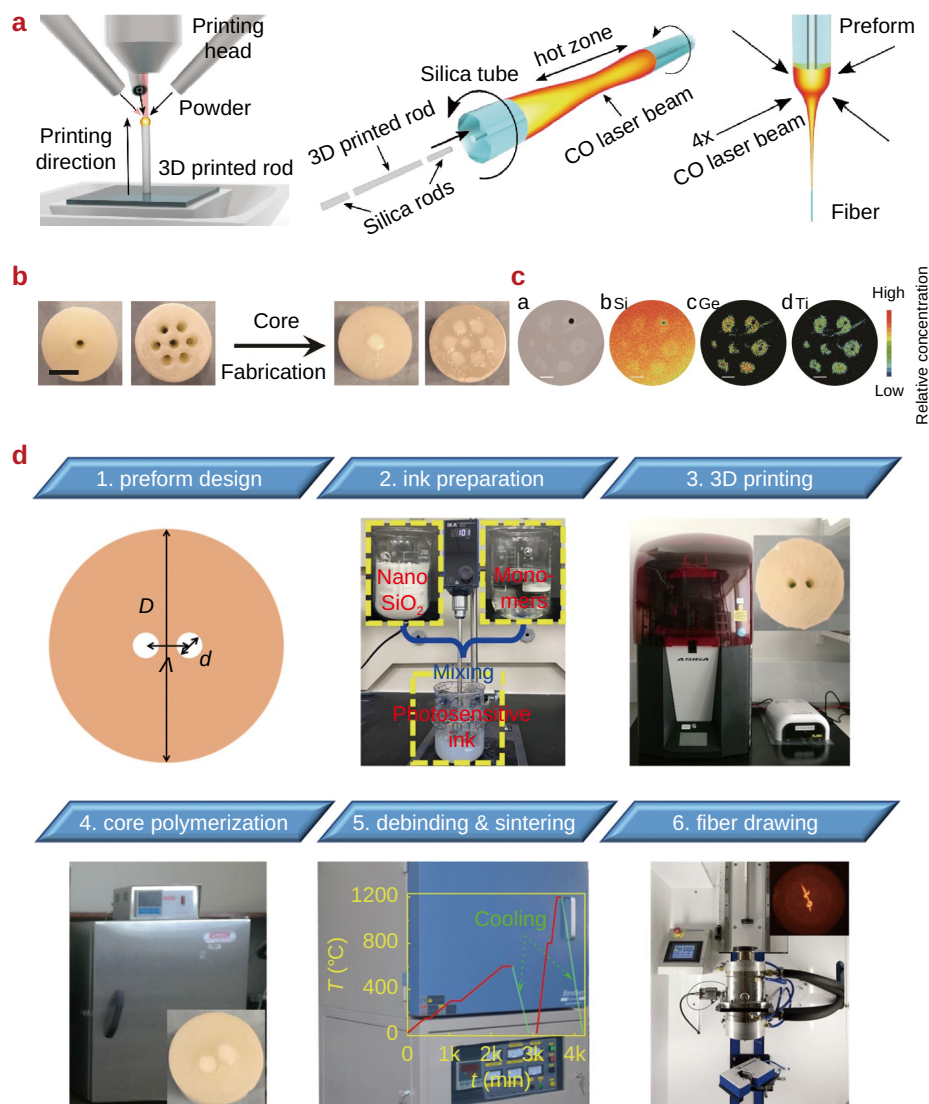


Fig. 7 | (a) 3D printing of the core material using a CO₂ laser, sleeving the rod in a silica tube for preform assembly, and fiber drawing using a CO laser-based tower with four horizontal beams symmetrically heating the preform. (b) Images of the 3D printed preforms (left) and subsequently filled cores (right). (c) Cross-sectional view of 7 cores BEDF, and electron probe micro-analysis-wavelength-dispersive X-ray fluorescence spectroscopy mappings of different elements from the cross section. (d) Course of the fabrication of 3D printed twin-core Bi/Er co-doped fiber (TCBEDF) from the design to the fiber drawing. Figure reproduced with permission from (a) ref.¹⁰³, Optica Publishing Group. (b, c) ref.¹⁰⁵, Light Publishing Group. (d) ref.¹⁰⁹, Elsevier B.V.

This near-term positioning is reinforced by the available attenuation data, which vary strongly with both the printing process and the measurement wavelength (ref.¹⁰⁷). Attenuation measured near a rare-earth absorption band can include intentional active-ion absorption and should not be interpreted entirely as background loss. A DIW-derived Er-doped fiber showed attenuation of 0.630 dB cm⁻¹ at 980 nm and 1.515 dB cm⁻¹ at 1535 nm. Er³⁺ absorption contributes to both values, together with parasitic absorption from residual hydroxyl and organic species. Early DLP-derived silica fibers showed 0.134 dB cm⁻¹ at 532 nm, 0.139 dB cm⁻¹ at 633 nm and 1.14 dB cm⁻¹ at 1550 nm. Later DLP-derived Bi/Er-doped and twin-core fibers exhibited attenuations

0.087 dB cm⁻¹ at 1300 nm and 0.031 dB cm⁻¹ at 1600 nm, respectively. Reported Selective Laser Sintering (SLS)-derived fibers exhibited losses of 23 dB m⁻¹ and 0.083 dB cm⁻¹ at 800 nm. LPD-derived fibers achieved 0.032 dB cm⁻¹ across 400–1000 nm for Ti-doped silica and 0.045 dB cm⁻¹ at 1550 nm for Er/Al-doped silica, respectively. The process dependence of these values reflects differences in feedstocks and thermal histories. DIW and DLP require binder removal and densification, so residual hydroxyl, carbon and interparticle voids can dominate parasitic absorption and scattering. SLS and LPD rely on localized melting, which reduces binder-related contamination but can introduce porosity, compositional nonuniformity and core-cladding interface

defects. Wavelength-resolved measurements and separation of active-ion absorption from baseline attenuation are therefore essential for meaningful process comparison.

2.3.2 Applications: macroscopic waveguides and fiber-tip integration

Digital fabrication provides a route to active fibers at two different structural scales: drawn fibers with additively manufactured active cores, and fiber-tip microstructures for localized sensing. For drawn active-fiber applications, research focuses on validating the reliability of active media fabricated via additive manufacturing during lasing or broadband-emission operation, while leveraging this technology's geometric freedom to achieve functional integration. Maniewski et al.¹⁰⁹ utilized the LPD process to fabricate an $\text{Er}^{3+}/\text{Al}^{3+}$ co-doped silica core rod, which was subsequently drawn into a single-mode EDF. By constructing a F-P resonant cavity using the Fresnel reflections from the cleaved end-faces of the fiber, they achieved a slope efficiency of 9.4% under 976 nm pumping. This result verifies that additive manufacturing can produce rare-earth-doped silica fibers capable of supporting laser operation. In addition to laser demonstration, 3D-printed active fibers have also been explored for combining broadband emission with structural sensing functions. Luo et al.¹⁰⁹ fabricated a TCBEDEF using 3D printing technology (Fig. 7(d)). The fiber exhibited ultra-broadband polarized NIR emission covering 950–1600 nm under 830 nm pumping. By utilizing the twin-core structure, an MZI based on an SMF-TCBEDEF-SMF configuration was constructed for multi-parameter sensing, including temperature, refractive index, tensile force, and bending. These results demonstrate the potential of 3D-printed active fibers as integrated platforms for broadband emission and sensing in future networked sensing systems.

As sensing requirements evolve toward miniaturization and multifunctional integration, the direct construction of active functional units on fiber end-faces (lab-on-fiber) using two-photon polymerization (TPP) printing technology offers a new route to miniaturized precision sensing. Pathak et al.¹¹⁰ utilized TPP to integrate an active polymer micro-ring resonator, doped with $\text{NaYF}_4: \text{Yb}^{3+}/\text{Er}^{3+}$ upconversion nanoparticles, onto the end-face of an SMF. By combining whispering gallery mode resonance with upconversion fluorescence characteristics, they achieved high-resolution temperature monitoring. Also using fiber-tip microprinting of luminescent materials, Manzani et al.¹¹¹ focused on the spectroscopic response of specific chemical components by micro-printing polymer structures loaded with Eu(III) complexes onto fiber end-faces. Through fluorescence intensity ratio technology, a high relative sensitivity of $5.0\% \text{ K}^{-1}$ was achieved within the temperature range of 296–363 K. Moving from single-parameter thermometry to more complex environmental monitoring, Aslani et al.¹¹² reported a multifunctional fiber-tip sensing

platform integrated with lanthanide fluorophores (such as europium complexes). Through 3D micro-printing, they constructed five distinct microstructures on the fiber end-face, including woodpile structures, F-P cavities, and disc and annular geometries. By leveraging the narrow emission bandwidth and long lifetime of lanthanide fluorophores, this platform enabled simultaneous monitoring of temperature, redox status, and ambient refractive index. Overall, these studies show that digital fabrication is expanding active optical fibers from conventionally drawn gain media toward integrated fiber platforms that combine emission, lasing, and sensing functions.

The preceding demonstrations confirm the functional potential of 3D-printed active fibers, but they also reveal a substantial gap between compact sensing devices and long-range gain components. Compared with mature vapor deposition processes such as MCVD, additive manufacturing based on photopolymerization (e.g., DLP, stereolithography) or DIW typically relies heavily on slurries or photosensitive resins containing organic binders¹⁰⁶. During subsequent debinding and high-temperature sintering, residual hydroxyl groups ($-\text{OH}$) and carbon impurities that are difficult to eliminate completely induce high parasitic absorption losses in the NIR communication bands¹¹³. Furthermore, the microscopic staircase effect inherent to layer-by-layer printing, together with interfacial defects formed during fiber drawing, can increase Rayleigh scattering. Together, these factors cause the loss of current 3D-printed silica fibers to remain at the dB/m level, which is far above the ultralow loss levels achieved by conventional optical fibers¹⁰⁷. Moreover, the mismatch of thermal expansion coefficients (TECs) among multi-component materials during high-temperature fiber drawing can lead to structural distortions at the core-cladding interface. These factors further limit the energy conversion efficiency and beam quality in long-range signal amplification and high-power laser oscillation. Consequently, the current macroscale applications of 3D-printed active fibers are largely confined to short-range specialty sensing or the preliminary verification of conceptual light sources. Progress toward high-gain amplifiers and high-power lasers will require purer printable inks, improved decarbonization and dehydroxylation, and hybrid fabrication strategies. These areas define the key technical gaps that must be addressed before 3D-printed active fibers can be used reliably in low-loss amplification and laser applications.

To provide a systematic overview of the sensing capabilities discussed above, Table 3 outlines the performance profiles of emerging active fiber sensors. It specifically details how the combined design of dopant systems and waveguide structures supports applications ranging from radiation monitoring to lab-on-fiber multiphysics sensing.

In summary, the integration of 3D printing technology has enabled a flexible evolution of active functional units, ranging from macroscopic waveguides to micro- and

Table 3 | Key performance parameters of emerging active fiber sensors

Sensing target	Dopant system	Fiber structure	Application highlight	Ref.
Temperature, Vibration	Er/Yb co-doped	Thin-core fiber	Temperature sensitivity of 94.70 pm/°C. Broadband vibration response of 1–48 kHz	ref. ^{68,69}
Partial discharge	Ce/Tb co-doped	Large-core fiber (57/205 μm core/cladding)	High response sensitivity of 0.22 ns-V/pC	ref. ⁷²
Carbon dioxide	Tm ³⁺ -doped	Not specified	Ultra-low CO ₂ detection limit of 190 ppb	ref. ⁷³
Torsion	Er ³⁺ -doped	Three-core fiber	High torsion sensitivity of 0.019 nm/°	ref. ⁹⁹
Magnetic field	Tb ₂ O ₃ nanofilm	Long-period fiber grating	Magnetic field sensitivity of 0.17 nm/mT	ref. ¹¹⁴
Radiation dose	Ce-doped	Microtapered fiber	Linear dose rate monitoring range of 0.5–170 mGy/s	ref. ⁵⁷
Bending, Temperature	Bi/Er co-doped	Dual-core fiber	Upward bending sensitivity of 207.00 nm/mm. Temperature sensitivity of 0.05 nm/°C	ref. ¹⁰⁹
Multiphysics monitoring	Eu(III) complex	Fiber-tip microstructure	High relative temperature sensitivity of 5.0%/K	ref. ¹¹¹

nanoscale fiber tips. Specifically, the lab-on-fiber integration mode, facilitated by processes such as TPP, leverages the geometric anisotropy of micro-nanostructures to provide a novel methodology for addressing cross-sensitivity issues in multi-parameter sensing. Although this approach shows clear advantages in micro- and nanoscale sensing, 3D-printed active fibers still face major limitations in maintaining high-Q lasing or achieving long-range high-gain compensation. These limitations are primarily attributed to material impurities and interface scattering losses, which remain difficult to eliminate within current additive manufacturing processes. However, the design freedom offered in constructing non-standard waveguide profiles and integrating heterogeneous materials has already established a clear technological advantage in compact, highly customized, short-range sensing scenarios. Overall, additive manufacturing shifts part of the design emphasis from long-distance gain media toward compact, integrated sensing platforms.

3 Conclusions and perspectives

3.1 Key bottlenecks

The three routes reviewed above have advanced active fibers from established gain media toward more integrated sensing units, but each route still faces distinct bottlenecks before large-scale deployment. Regarding rare-earth-doped systems, single-ion and multi-ion co-doped fibers have achieved gain coverage from the visible to the mid-infrared spectrum, but their practical deployment still faces several challenges. In sensing networks, the long-term reliability of the gain medium remains a critical bottleneck. Although tolerance to extreme environments can be improved at the laboratory scale through compositional regulation and pre-treatment, these strategies still require systematic validation and standardization. Such standardization is essential to meet the rigorous industrial requirements for device longevity and performance consistency. Furthermore, another challenge lies in the efficient utilization of pump

resources in large-scale sensing arrays, where achieving on-demand dynamic gain allocation across multiple nodes under limited pump power remains a significant engineering challenge. This issue will need to be addressed as active optical fibers are integrated into networked architectures.

At the structural design level, air-hole arrays and annular doping profiles have proven effective in regulating modal gain and optical-field distributions^{77,86}. However, most current designs remain limited to the optimization of transverse cross-sections. A remaining challenge is the development of axially varying fibers, in which geometric features or dopant distributions change predictably along the propagation direction. Such fibers could cascade functions such as mode evolution, dispersion management and nonlinear regulation along a single fiber axis, potentially simplifying complex sensing architectures. Their practical implementation, however, requires greater fabrication accuracy and reproducible longitudinal profiles. Beyond fabrication precision, mechanical integrity presents another structural constraint. Microstructured fibers also face mechanical-integrity challenges because thin glass webs, internal holes, asymmetric cores and multimaterial interfaces can concentrate stress. These features may reduce tolerance to bending, vibration, impact and thermal shock. Their use in complex field environments therefore requires proof testing; tensile, repeated-bend, vibration and thermal-shock measurements; and evaluation after splicing and packaging. Such structures must preserve the required optical function while retaining sufficient wall thickness and avoiding excessive stress concentrations.

For additively manufactured active fibers, a related challenge is translating geometric flexibility into repeatable and calibrated device performance^{109,111}. Current research still focuses mainly on process feasibility and proof-of-concept demonstrations. Progress toward practical sensing applications therefore requires improved printing precision, material-interface control and device packaging. The process-dependent loss spectra further show that no single purification strategy applies to all additive processes. For slurry- and resin-based printing, reducing parasitic absorption requires

high-purity feedstocks and optimized debinding, dehydroxylation and densification. Reducing scattering additionally requires uniform particle packing, low porosity, smooth printed interfaces and controlled shrinkage during drawing. For locally melted processes, the more relevant controls include porosity, volatilization, compositional uniformity, frozen-in stress and core-cladding interface quality. Loss should therefore be evaluated spectrally in relation to the intended device length and operating wavelength rather than a single attenuation value. Low initial loss alone is insufficient, because the same process-dependent defects may also compromise long-term stability. Residual hydroxyl or carbon species may contribute to pump-induced degradation, while pores, frozen-in stress, dopant redistribution and heterogeneous interfaces may promote optical drift during thermal or environmental exposure. Reliability should therefore be assessed through long-term optical-pumping tests, thermal cycling and damp-heat testing. Irradiation testing should also be included for applications involving ionizing-radiation exposure. These measurements should track attenuation, emission, gain and spectral stability rather than only the initial transmission loss.

Despite their different fabrication constraints, both routes ultimately depend on process consistency. For microstructured fibers, repeatability requires control over preform geometry, wall thickness, dopant distribution, drawing stability, splicing and packaging. Additively manufactured fibers require additional control over feedstock rheology and purity, printing resolution, debinding, sintering and preform shrinkage. In-line dimensional monitoring, chemical and optical inspection, and batch-level statistics are therefore needed to quantify unit-to-unit variation and fabrication yield. Without such controls, design freedom alone cannot ensure reproducible sensing performance.

3.2 Outlook

In IoE-oriented sensing networks, optical fibers are increasingly expected to link distributed physical objects, sensing units, and information systems while supporting signal transmission, local amplification, and environmental transduction¹³. Within this architecture, densely deployed sensing units are expected to become integral components of distributed sensing infrastructure. Accordingly, the role of optical fibers is expanding beyond passive transmission to encompass both signal delivery and environmental readout. In this context, the flexible control offered by 3D printing technology¹⁰⁶ at both the material and structural levels provides a key enabling mechanism for miniaturized and functionally customized sensing units. This capability is well aligned with the need for highly integrated, customizable and deployable sensing units in distributed physical environments. From a broader perspective, the core value of additive manufacturing for fiber-optic sensors lies not in the realization of any specific structure, but in the ability to

design fiber sensors¹¹⁵ around target responses rather than relying only on existing fiber geometries. This approach marks a transition from ‘identifying usable characteristics within existing fiber structures’ to ‘inverse-designing and directly forming units based on target sensing requirements.’ This design freedom could support compact active-fiber sensors in distributed sensing infrastructure, where they may serve as local sensing front ends. Realizing this design freedom at network scale, however, requires the three technological routes to be evaluated through coupled link, node, timing and resource budgets. Composition engineering mainly determines gain efficiency, spectral coverage and pump demand. Microstructural engineering influences sensitivity, cross-sensitivity and modal coupling. Additive manufacturing affects device footprint, packaging complexity and manufacturing yield. A viable active sensing unit must satisfy these budgets simultaneously. Improving one metric at the expense of excessive loss, pump power, calibration burden or unit-to-unit variation may not improve the sensing network as a whole.

Against these system-level requirements, 3D-printed microstructured active fibers provide a distinctive implementation path for constructing multifunctional, integrated sensing waveguides. Conventional preform fabrication constrains the integration of microstructural design with active doping. Additive manufacturing can relax some of these geometric limitations. By combining digital modeling with material-composition control, additive manufacturing can integrate SDM architectures with customized gain-media distributions within a single fiber. Such an integrated waveguide may simultaneously serve as a carrier for parallel signal transmission, a sensing unit, and an active medium for signal compensation in future fiber-optic sensing networks. Beyond integrating these functions, greater structural flexibility allows the internal functional distribution of these waveguides to be tailored to deployment requirements rather than constrained to uniform, repetitive patterns.

The resulting integration potential must nevertheless be weighed against the reliability constraints associated with microstructural design and 3D printing. More complex structures can provide additional sensing channels and local active functions, but they also increase sensitivity to dimensional errors, interfacial defects and packaging stress. Future designs should therefore be optimized jointly for optical performance, mechanical tolerance and manufacturability.

These constraints distinguish near-term technologies from longer-term prospects. Composition-engineered active fibers are the most mature for sources, amplifiers and selected sensing functions. Established microstructured designs are nearer-term candidates when fabrication and packaging meet application-specific tolerances. Hybrid manufacturing may extend this range by combining conventionally drawn low-loss active fibers with additively manufactured preforms, localized functional regions or fiber-tip structures. This approach preserves the transmission quality

and mechanical maturity of established fibers while using additive methods where geometric customization provides a clear value. Fully printed, long-length and low-loss active fibers remain a longer-term objective that depends on improved material purity, structural fidelity, long-term reliability and process yield.

Looking ahead, as these technological routes mature, the role of active fibers in fiber-optic sensing networks may expand beyond gain compensation toward more task-specific sensing and signal-management functions. At present, a central role of active fibers in networked sensing systems is to provide online amplification for long-distance transmission and maintain a sufficient SNR. However, their gain characteristics remain largely fixed once fabricated. In the future, the combined design of gain-medium distribution and microstructure could enable gain allocation to be tailored among sensing units. If validated at the system level, this shift could help balance the detection SNR across sensing units in large-scale sensing arrays. The long-term goal is therefore not a single universal active fiber, but a design library of active-fiber components in which composition, waveguide geometry, and fabrication route are selected according to the sensing parameter, network position, and required signal-management function. Viewed across these development horizons, the three routes operate at complementary levels rather than as separate technological endpoints. Composition engineering defines energy conversion and stability, microstructural engineering controls field distribution and measurand interaction, and additive manufacturing extends spatial placement and integration. Their convergence therefore supports a shift from fibers used mainly as gain media toward active sensing units that combine environmental transduction with local signal generation, amplification, spectral conversion or optical-field control.

References

- Weill R, Bekker A, Levit B et al. Bose–Einstein condensation of photons in an erbium–ytterbium co-doped fiber cavity. *Nat Commun* 10, 747 (2019).
- Guo H, Li T, Yan FP et al. Few-mode erbium-doped fiber amplifier with high gain and low differential modal gain for mode-division-multiplexed systems. *J Lightwave Technol* 41, 6657–6663 (2023).
- Gao H, Hu HF, Zhan QW. Tailoring temperature response for a multimode fiber. *Opto-Electron Sci* 4, 240004 (2025).
- Wei XR, Liang YZ, Zhang XH et al. Multi-resonance enhanced photothermal synergistic fiber-optic Tamm plasmon polariton tip for high-sensitivity and rapid hydrogen detection. *Opto-Electron Sci* 4, 240029 (2025).
- Zalevsky Z. Fiber-based wearable sensors for bio-medical monitoring. *Opto-Electron Adv* 8, 250026 (2025).
- Gao W, Fan WH, Ju P et al. Effective suppression of mode distortion induced by stimulated Raman scattering in high-power fiber amplifiers. *High Power Laser Sci Eng* 9, e20 (2021).
- Varshney AK, Mainuddin, Singhal G et al. High power lasers for directed energy applications: Developments and challenges. *Infrared Phys Technol* 136, 105064 (2024).
- Onodera N, Tsuji K, Saruwatari M. Up to 8-GHz ultrafast multi-wavelength routing operation of active birefringent fiber loop filter/interleaver using a traveling-wave-type phase modulator. *Opt Rev* 12, 359–362 (2005).
- Romano C, Panitzek D, Lorenz D et al. High-power thulium-doped fiber MOPA emitting at 2036 nm. *J Lightwave Technol* 42, 394–398 (2024).
- Vařák P, Peterka P, Kamrádek M et al. Fluorescence lifetime of highly rare-earth-doped silica optical fibers – the influence of composition and fabrication processing. In *2024 24th International Conference on Transparent Optical Networks (ICTON)* 1–4 (IEEE, 2024). <http://doi.org/10.1109/ICTON62926.2024.10647713>.
- Li J, Zhang MJ. Physics and applications of Raman distributed optical fiber sensing. *Light Sci Appl* 11, 128 (2022).
- Song KY. Optimizing multi-parameter distributed fiber sensors: a hybrid Rayleigh-Brillouin-Raman System approach. *Light Sci Appl* 13, 46 (2024).
- Liu ZX, Xie JW, Zhang YW et al. A review of optical fiber integrated sensing and communication systems. *Sci China Inf Sci* 69, 160302 (2026).
- Vařák P, Kašík I, Peterka P et al. Heat treatment and fiber drawing effect on the luminescence properties of RE-doped optical fibers (RE = Yb, Tm, Ho). *Opt Express* 30, 10050–10062 (2022).
- Mao D, Wang HQ, Zhang HZ et al. Synchronized multi-wavelength soliton fiber laser via intracavity group delay modulation. *Nat Commun* 12, 6712 (2021).
- Karmakar D, Dana K, Ghosh S et al. An advanced fabrication method for Yb³⁺-Doped optical fibers featuring AlPO₄ core glass. *Ceram Int* 50, 41044–41056 (2024).
- Tang YT, Luo X, Dong FL et al. All-fiber Mid-infrared enhanced supercontinuum generation in an Erbium-doped ZBLAN fiber amplifier. *J Lightwave Technol* 41, 2855–2861 (2023).
- Chang YB, Pei L, Wang JS et al. Strain and curvature optical fiber laser sensor based on an accurate RI-regulated FMF with high modal power balance. *Opt Commun* 531, 129183 (2023).
- Yang HN, Dong B, Zhao W et al. Er/Yb codoped double clad fiber modal interferometer and its application as fiber sensor. *J Lightwave Technol* 37, 2681–2685 (2019).
- Tenbrake L, Faßbender A, Hofferberth S et al. Direct laser-written optomechanical membranes in fiber Fabry-Perot cavities. *Nat Commun* 15, 209 (2024).
- Li W, Liu W, Deng Y et al. Functional Yb-doped fiber with a bat-type refractive index distribution for beyond kilowatt all-fiber single-frequency laser amplification. *Light Sci Appl* 14, 271 (2025).
- Matte-Breton C, Ryf R, Fontaine NK et al. Modeling and characterization of cladding-pumped erbium-ytterbium co-doped fibers for amplification in communication systems. *J Lightwave Technol* 38, 1936–1944 (2020).
- Sennoun L, Florea I, Orange F et al. Enhanced optical fiber fabrication via the MCVD process incorporating pre-synthesized ZrO₂ nanoparticles. *Opt Mater* 164, 117015 (2025).
- Iskhakova LD, Milovich FO, Likhachev ME et al. Analysis of elemental distributions and phase separation in rare-earth-doped silica-based fiber preforms and optical fibers. *J Non-Cryst Solids* 554, 120616 (2021).
- Dai XY, Shi JL, Zhao XF et al. Detection of riboflavin concentration by sol-gel silica coated dual-peak long period fiber grating sensor. *Opt Express* 32, 36286–36297 (2024).
- Dhar A, Choudhury N, Sen R. Advancements in fabrication technology for rare-earth doped optical fibers: A retrospective analysis. *Opt Commun* 577, 131463 (2025).
- Feng NN, Lu M, Sun SQ et al. Light-emitting device based on amplified spontaneous emission. *Laser Photonics Rev* 17, 2200908 (2023).

28. Kang ZX, Sun J, Bai YL et al. Twin-core fiber-based erbium-doped fiber laser sensor for decoupling measurement of temperature and strain. *IEEE Sens J* **15**, 6828–6832 (2015).
29. Wang F, Lin SY, Qu YC et al. High-sensitivity all-optical phase modulation based on Fabry–Perot interferometer integrated with Er/Yb co-doped fiber and ultraviolet glue. *J Lightwave Technol* **43**, 3464–3471 (2025).
30. Liang LL, Qin X, Zheng KZ et al. Energy flux manipulation in upconversion nanosystems. *Acc Chem Res* **52**, 228–236 (2019).
31. Stone J, Burrus CA. Neodymium -doped silica lasers in end -pumped fiber geometry. *Appl Phys Lett* **23**, 388–389 (1973).
32. Chahal S, Xiao BY, Grant J et al. Ce³⁺-doped chalcogenide glass fibre for laser beyond 4 microns wavelength: Glass material-integrity. *Opt Mater* **166**, 117219 (2025).
33. Tench RE, Delavaux JM, Walasik W et al. 2 μ m watt-level fiber amplifiers, lasers, and ASE sources pumped by broadband ASE pumps. *J Lightwave Technol* **42**, 8881–8888 (2024).
34. Huang CH, Dong YH, Huang Y et al. Compact and high-sensitivity bismuth-doped silica optical fiber weak magnetic sensor. *IEEE Sens J* **25**, 6326–6335 (2025).
35. Zheng JJ, Dong YH, Pan XP et al. Ultra-wideband and flat-gain optical properties of the PbS quantum dots-doped silica fiber. *Opt Express* **27**, 37900–37909 (2019).
36. Wang WQ, Yang YY, Wen JX et al. Formation of E-band luminescence-active centers in bismuth-doped silica fiber via atomic layer deposition. *Opt Express* **32**, 8723–8735 (2024).
37. Huang CH, Dong YH, Huang Y et al. Efficient Tb-O-Al coupling via atomic layer engineering for weak magnetic field detection. *Ceram Int* **51**, 56272–56280 (2025).
38. Dong ZP, Yao YJ, He MY et al. Direct generation of a 635 nm red random laser based on praseodymium (Pr)-doped ZBLAN fiber. *Opt Lett* **49**, 2497–2500 (2024).
39. Unger S, Leich M, Schwuchow A et al. Absorption and emission properties of thulium doped glasses in optical fibers. *Opt Mater Express* **15**, 446–464 (2025).
40. Wang B, Wen JX, Chen ZR et al. Radiation resistance of erbium-doped fibers for space laser communication applications. *Chin J Lasers* **52**, 0106005 (2025).
41. Wang YM, Luo YH, Wen JX et al. Negative effect of bismuth nanoparticles upon the luminescent properties of bismuth active centers in bismuth doped fiber. *Opt Laser Technol* **187**, 112844 (2025).
42. Topper B, Meehan B, Baldus B et al. Temperature-dependent fluorescence study of ytterbium-doped borophosphosilicate fiber for optical cooling applications. *J Opt Soc Am B* **43**, 573–580 (2026).
43. Wang Y, Thipparapu NK, Richardson DJ et al. Ultra-broadband bismuth-doped fiber amplifier covering a 115-nm bandwidth in the O and E bands. *J Lightwave Technol* **39**, 795–800 (2021).
44. Zheng JJ, Peng Y, Li W et al. Comparative study of high-power single-frequency fiber amplifiers at 1.5 μ m based on absorption control of Er/Yb co-doped active fiber. *Opt Laser Technol* **183**, 112380 (2025).
45. Dong YH, Zhang M, Zhang HY et al. Enhanced fluorescence and gain characteristics of PbS doped silica fiber with PbSe nano-semiconductor co-doping. *Opt Fiber Technol* **80**, 103370 (2023).
46. Yang Q, Hu BY, Gao J et al. Effective stabilization of photobleaching of BAC-Si in bismuth- and erbium-codoped optical fibers by 830 nm laser repeated pumping. *Chin Opt Lett* **23**, 010604 (2025).
47. Chen Y, Wang WQ, Yang YY et al. Near 0.5 dB gain per unit length in O-band based on a Bi/P co-doped silica fiber via atomic layer deposition. *Opt Express* **31**, 14862–14872 (2023).
48. Li WZ, He L, Ju W et al. Over 100 W C + L band wavelength-tunable Er/Yb co-doped fiber amplifier with 75 nm bandwidth. *Opt Fiber Technol* **94**, 104371 (2025).
49. Li TT, Wen JX, Wu Y et al. Influences of Bi and Yb ions on the emission efficiency of an Er-doped silica optical fiber. *Opt Mater Express* **12**, 3918–3929 (2022).
50. Prasanth M, Ravi N, Thyagarajan K. Erbium-ion-doped bismuth borate glasses for high optical gain NIR fiber laser applications. *ECS J Solid State Sci Technol* **13**, 026004 (2024).
51. Liu HY, Wen JX, Dong YH et al. Bandwidth extension to 1627 nm of over 20 dB gain in an erbium-doped silica fiber via two-photon absorption. *Opt Express* **32**, 8937–8949 (2024).
52. Miluski P, Markowski K, Kochanowicz M et al. Tm³⁺/Ho³⁺ profiled co-doped core area optical fiber for emission in the range of 1.6–2.1 μ m. *Sci Rep* **13**, 13963 (2023).
53. Fan DS, Luo YH, Yan BB et al. Ionizing radiation effect upon Er/Yb co-doped fibre made by in-situ nano solution doping. *J Lightwave Technol* **38**, 6334–6344 (2020).
54. Zhang YT, Wang GC, Zhao T et al. Photobleaching effects and influencing mechanisms of radiation-induced darkening in Erbium-Ytterbium co-doped fibers with different wavelengths of lasers. *J Lightwave Technol* **43**, 3899–3905 (2025).
55. Zhang YQ, Yang Q, Chu YS et al. Observation of defect-modulated photobleaching in bismuth-erbium co-doped fibers. *Opt Lett* **50**, 5941–5944 (2025).
56. Dong YH, Fang G, Dong QN et al. Gamma irradiation-induced enhancement of Pb-related near-infrared luminescence in PbS/Al co-doped silica fiber. *Opt Express* **32**, 30040–30052 (2024).
57. Fricano F, Morana A, Hoehr C et al. Pre-irradiation influence on proton radioluminescence responses of sol-gel optical fibers. *IEEE Trans Nucl Sci* **72**, 2059–2065 (2025).
58. Li YC, Li YY, Cai MZ et al. Enhanced tunable mid-infrared emissions by controlling rare earth ion energy transfer processes in multifunctional multiphase solids. *J Eur Ceram Soc* **41**, 5981–5989 (2021).
59. Wang T, Huang FF, Ren GY et al. Broadband 2.9 μ m emission and high energy transfer efficiency in Er³⁺/Dy³⁺ co-doped fluoroaluminates glass. *Opt Mater* **75**, 875–879 (2018).
60. Sun M, Pang YL, Li JL et al. Silica-based Er: YAG nanocrystal composite fibers enabling S+C+L broadband tunable lasers. *Adv Opt Mater* **14**, e03634 (2026).
61. Cai YZ, Yan FP, Qin Q et al. Thulium-doped fiber laser with wavelength switchable output and its utilization in temperature sensing. *Infrared Phys Technol* **149**, 105923 (2025).
62. Yu CH, Yan FP, Yang DD et al. Stable four-wavelength switchable narrow-linewidth thulium-holmium co-doped fiber laser based on dual-cascaded PM-FBGs. *IEEE Photonics J* **18**, 1500306 (2026).
63. Meng Y, Li SN, Gao CN et al. Study on the characteristics of Fabry-Perot resonator based on erbium-doped fiber dynamic grating and fiber Bragg grating. *Phys Lett A* **577**, 131464 (2026).
64. Panitzek D, Romano C, Písařík M et al. Temperature and pump modulation investigation of an Er: Yb co-doped fiber laser with optimized SWaP. *Opt Express* **33**, 3851–3860 (2025).
65. Puttnam BJ, Luís RS, Huang YT et al. 321 Tb/s E/S/C/L-band transmission with E-band bismuth-doped fiber amplifier and optical processor. *J Lightwave Technol* **42**, 4006–4012 (2024).
66. Wang WQ, Wen JX, Dong YH et al. Ultra-wideband and flat gain bismuth-doped fiber amplifier based on double pass configuration. *IEEE Photonics Technol Lett* **38**, 49–52 (2026).
67. Zhang CZ, Jia ZX, Wang JJ et al. Optical amplification ranging from 1600 to over 1680 nm in thulium-doped fluorotellurite glass fibers with a terbium-doped cladding. *Opt Lett* **50**, 1413–1416 (2025).
68. Fu XH, Huang ZX, Zhou JH et al. A dual-parameter sensing system for temperature and curvature based on Nano-EYDF and in-line cascaded Mach-Zehnder interferometer. *Opt Laser Technol*

- 163, 109353 (2023).
69. Fu XH, Tang J, Miao YD et al. A ring cavity laser sensor for measuring different vibration frequencies and driving voltages. *Infrared Phys Technol* **149**, 105920 (2025).
70. Huang ZX, Luo YH, Wen JX et al. Radiation enhanced sensitivity of temperature and curvature sensor based on Bi/Er Co-doped fibre with ultra-broadband emission. *Measurement* **254**, 117936 (2025).
71. Fricano F, Vallifuoco R, Lambert D et al. Sensitivity enhancement of tapered cerium-doped optical fibers for dosimetry applications. *IEEE Trans Nucl Sci* **72**, 1130–1136 (2025).
72. Hu CY, Huang Y, Deng CL et al. An innovative fluorescent fiber sensor based on Ce/Tb co-doped silica fiber for partial discharge detection. *IEEE Sens J* **23**, 6939–6947 (2023).
73. Wang FP, Han Z, Zhang JG et al. Highly sensitive carbon dioxide detection based on enhanced photoacoustic spectroscopy with a thulium-doped fiber amplifier. *Chin Opt Lett* **23**, 023001 (2025).
74. Rasekh F, Kamel NG, Bornadel M et al. Ultra-narrow homogeneous linewidths of erbium-doped silica glass fibers at millikelvin temperatures: magnetic field and temperature dependence. *Optica Quantum* **4**, 63–72 (2026).
75. Russell P. Photonic crystal fibers. *Science* **299**, 358–362 (2003).
76. Wang F, Wang M, Shao CY et al. Highly fluorine and ytterbium doped polarization maintaining large mode area photonic crystal fiber via the sol-gel process. *Opt Express* **29**, 41882–41893 (2021).
77. Xiong RL, Chen W, Wang F et al. High-gain and low-DMG mode amplification characteristics based on two-layer ring-core erbium-doped fiber. *Opt Fiber Technol* **93**, 104240 (2025).
78. Lebreton A, Mélin G, Bordaïs S et al. Design optimization of 12-core amplifier based on erbium ytterbium co-doped fiber for spatial multiplexed transmission system. *J Lightwave Technol* **41**, 462–476 (2023).
79. Choudhury N, Shekhar NK, Dhar A et al. Graded-index ytterbium-doped optical fiber fabricated through vapor phase chelate delivery technique. *Phys Status Solidi (A)* **216**, 1900365 (2019).
80. Martín JC, Berdejo V, Vallés JA et al. Study of the use of methanol-filled Er-doped suspended-core fibres in a temperature-sensing ring laser system. *Laser Phys* **23**, 105107 (2013).
81. Chu YS, Tian Y, Fan DS et al. Fabrication and characterization of birefringent bismuth and erbium co-doped photonic crystal fiber for broadband polarized near infrared emission. In *Conference on Lasers and Electro-Optics JW2A*. 107 (Optica Publishing Group, 2019). https://doi.org/10.1364/CLEO_AT.2019.JW2A.107.
82. Mehta A, Rehan M, Rastogi V. Erbium-doped circular photonic crystal fiber design for the amplification of 20 OAM modes. *J Opt Soc Am B* **38**, F138–F144 (2021).
83. Liu DD, Chen W, Wang F et al. High-efficiency high-mode-purity cylindrical vector beam based on ring-core Yb-doped fiber. *IEEE Photonics Technol Lett* **37**, 187–190 (2025).
84. Ren JJ, Qi YF, Yu T et al. Theoretical analysis and optimization on nested-ring doped LMA-TDFs in the power scaling of short-wavelength TDFO. *Phys Scr* **100**, 035557 (2025).
85. Chang YB, Pei L, Zheng JJ et al. Demonstration of an all-fiber cladding-pumped FM-EDFA with low differential modal gain. *Opt Laser Technol* **155**, 108446 (2022).
86. Wu Y, Wen JX, Tang FZ et al. Orbital-angular-momentum fluorescence emission based on photon–electron interaction in a vortex field of an active optical fiber. *Nanophotonics* **12**, 43–53 (2023).
87. Tan F, Chen DX, Ge SS et al. Luminescence properties and application of near-infrared Er³⁺-doped bismuth germanate laser glass. *Opt Commun* **591**, 132167 (2025).
88. Matte-Breton C, Chen H, Fontaine NK et al. Demonstration of an erbium-doped fiber with annular doping for low gain compression in cladding-pumped amplifiers. *Opt Express* **26**, 26633–26645 (2018).
89. Jung Y, Kang QY, Sidharthan R et al. Optical orbital angular momentum amplifier based on an air-hole erbium-doped fiber. *J Lightwave Technol* **35**, 430–436 (2017).
90. Perezcampos-Mayoral C, Gutiérrez-Gutiérrez J, Cano-Pérez JL et al. A tunable and switchable multi-wavelength erbium-doped fiber laser based on a curvature Mach–Zehnder interferometer filter using thin-core fiber. *Appl Sci* **14**, 11578 (2024).
91. Lu YH, Wen JX, Cao Y et al. Vortex fiber laser based on twisted high concentration doped active fiber. In *2024 22nd International Conference on Optical Communications and Networks (ICOON)* 1–3 (Harbin, 2024). <http://doi.org/10.1109/ICOON63276.2024.10648489>.
92. Alyshev S, Vakhrushev A, Umnikov A et al. Supermode lasing and light amplification in multicore bismuth-doped fiber. *Opt Express* **32**, 29214–29226 (2024).
93. De I, Gaur A, Rastogi V. Multimode erbium-doped fiber amplifier based on double-clad GeO₂-doped photonic crystal fiber supporting 38 orbital angular momentum modes. *J Lightwave Technol* **42**, 5650–5656 (2024).
94. Guo BF, Li WH, Gao SC et al. Five-orbital-angular-momentum-mode-group erbium-doped fiber amplifier with modal gain equalization. *Photonics Res* **14**, 274–285 (2026).
95. Wen TJ, Gao SC, Li W et al. Orbital angular momentum mode-multiplexed amplification and transmission based on a ring-core erbium-doped fiber. *J Lightwave Technol* **41**, 2116–2122 (2023).
96. He L, Qiu Q, Yin XK et al. Extended L-band 4-core Er/Yb co-doped fiber amplifier based on 1018 nm cladding pumping. *Opt Express* **31**, 25557–25570 (2023).
97. Zhao LJ, Liang RY, Xu ZN. Erbium-ytterbium co-doped photonic crystal fiber amplifier supporting amplification for orbital angular momentum. *Laser Phys* **32**, 075102 (2022).
98. Zhang MY, Zhao QC, Yan JY et al. Highly sensitive multiparametric sensors based on Mach–Zehnder interferometers via twin-core Yb-doped optical fibers. *IEEE Sens J* **25**, 37970–37980 (2025).
99. Serrano AIC, Galarza M, Leventoux Y et al. High-sensitivity torsion sensor based on Er³⁺-doped multicore fiber-ring laser. *IEEE Sens J* **26**, 305–311 (2026).
100. Li BY, Wu M, Liang YY et al. Multi-functional double rare-earth-doped ball sensor based on a hollow-core microstructure fiber. *Opt Lett* **44**, 2350–2353 (2019).
101. Zheng BL, Yang J, Qi FX et al. Fabrication of Yb-doped silica micro-structured optical fibers from UV-curable nano-composites and their application in temperature sensing. *J Non-Cryst Solids* **573**, 121129 (2021).
102. Camacho Rosales AL, Núñez-Velázquez M, Sahu JK. 3D printed Er-doped silica fibre by Direct Ink Writing. *EPJ Web Conf* **243**, 20002 (2020).
103. Maniewski P, Harvey CM, Mühlberger K et al. Rapid prototyping of silica optical fibers. *Opt Mater Express* **12**, 2426–2435 (2022).
104. Shi YW, Zhao N, Chen Y et al. Spectroscopic analysis of Nd/Al co-doped silica glass fabricated by laser additive manufacturing. *J Non-Cryst Solids* **604**, 122139 (2023).
105. Chu YS, Fu XH, Luo YH et al. Additive manufacturing fiber preforms for structured silica fibers with bismuth and erbium dopants. *Light Adv Manuf* **3**, 358–364 (2022).
106. Chekkaramkodi D, Ahmed I, Alam F et al. Review: 3D printing of optical fibers and optical fiber preforms. *J Mater Sci* **61**, 10799–10823 (2026).
107. Luo YH, Chu YS, Zhang JZ et al. 3D printing-based photonic waveguides, fibers, and applications. *Appl Phys Rev* **12**, 011322 (2025).
108. Maniewski P, Brunzell M, Barrett L, et al. Er-doped silica fiber laser made by powder-based additive manufacturing. *Optica* **10**, 1280–

- 1286 (2023).
109. Luo YH, Chu YS, Fu XH et al. 3D printing specialty multi-function twin core Bi/Er co-doped silica optical fibres for ultra-broadband polarized near infrared emission and sensing applications. *Opt Laser Technol* **168**, 109817 (2024).
 110. Pathak AK, Kulkarni S, Krishnaswamy S et al. Two-photon 3D printed active polymer ring resonators on the tip of optical fibers for temperature sensing. *Proc SPIE* **12951**, 1295121 (2024).
 111. Baltieri RS, Reupert A, Manzani D et al. Remote luminescent temperature sensing using 3D-printed Eu(III)-doped micropolymers at the tip of an optical fiber. *Adv Mater Technol* **10**, 2401877 (2025).
 112. Aslani V, Baghapour S, Warren-Smith SC et al. 3D microprinting of structures with lanthanide-based fluorophores on optical fibers for multiplexed sensing. *Adv Opt Mater* **14**, e02989 (2026).
 113. Dong LL, Bai JZ, Wan X et al. Effect of sintering condition on the attenuation of silica glasses fabricated by additive manufacturing. *Ceram Int* **49**, 39400–39408 (2023).
 114. Dong YH, Chen M, Huang CH et al. Magnetic field sensor based on nano-terbium-oxide coated long-period fiber grating. *IEEE Photonics Technol Lett* **37**, 1025–1028 (2025).
 115. Liu HH, Hu DJJ, Sun QZ et al. Specialty optical fibers for advanced sensing applications. *Opto-Electron Sci* **2**, 220025 (2023).

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Competing interests

The authors declare no competing financial interests.



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