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Original Research Article

Advances in specialty optical fiber technology for multidisciplinary applications

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Abstract: Continuous breakthroughs in waveguide structure design, material composition control and functional integration are transforming specialty optical fibers from conventional optical communication media into enabling technologies covering medicine, industry and defence. This paper systematically reviews the latest application progress of specialty optical fiber technology in two major areas: Medical and industrial. In the medical field, the focus is on the core role of optical fibers in biochemical analyser spectral analysis, holmium laser lithotripsy, endovenous laser ablation (EVLA) for varicose veins, and excimer laser coronary atherectomy (ELCA). In the industrial field, the paper analyses fiberbased precision ranging technology, the application of OPGW power cables in temperature monitoring of converter valves, and recent advances in distributed fiber-optic hydrophone technology. Incorporating the latest achievements in novel fiber technologies such as midinfrared fluoride fibers, multimaterial fibers, and hollowcore fibers, this review aims to provide a systematic reference framework for research and applications of specialty optical fibers in interdisciplinary domains.
Keywords: specialty optical fiber; interventional laser therapy; fiber-optic sensing; distributed hydrophone

1. Introduction

Since the birth of optical fiber technology in the mid-20th century, its low loss, high bandwidth and immunity to electromagnetic interference have laid the foundation of the optical fiber communication industry. However, with the rapid development of materials science and micronano processing technologies, the application boundaries of optical fibers have long surpassed traditional communication. Specialty optical fibers – through carefully designed core/cladding compositions, novel microstructured waveguides or integrated multimaterial functionalities – are driving the evolution of fiber technology from "passive transmission" to "active sensing" and "precise actuation", becoming core components supporting medical technological innovation, industrial intelligence upgrades, and defence security.

From a clinical perspective, optical fibers have become ideal carriers for minimally invasive interventional therapy. Whether it is pulsed laser transmission in urological holmium laser lithotripsy, energy delivery in vascular laser ablation or the photochemical action of excimer laser plaque ablation in cardiovascular intervention, specialty fibers play a critical role as "precise energy delivery vehicles". A 2025 review notes that the application of optical fibers in medicine has expanded to scenarios including endoscopic light transmission, atherosclerotic plaque ablation, and renal stone fragmentation. Meanwhile, fiber-optic sensing technology also provides a highly sensitive labelfree detection platform for biochemical analysis.

On the industrial front, optical fibers are not only signal transmission channels but also distributed sensing nerves. Technologies based on Brillouin scattering, Rayleigh scattering and fiber Bragg gratings have shown irreplaceable advantages in power system online monitoring, underwater acoustic detection and precision measurement. Especially in ultrahigh voltage direct current transmission, the thermal management of converter valves is directly linked to grid safety, and fiber-optic temperature measurement systems – thanks to their electrical insulation and electromagnetic immunity – have become the ideal technical solution for converter valve temperature monitoring.

This paper will systematically review the latest research progress and typical application cases of specialty optical fibers in the above two directions, and then outline future technical challenges and development trends.

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2. Medical applications of specialty optical fibers

Medical applications of specialty optical fibers can be divided into two broad categories: One is biochemical detection and clinical realtime monitoring based on fiber-optic sensors; the other is laser interventional therapy based on fiberbased energy delivery.

2.1. Fiber-optic biochemical sensors and spectral analysis

Fiber-optic biosensors (FOBs) have made rapid progress over the past decade. The core principle is to utilise the evanescent wave interaction between the fiber and target molecules, converting biochemical reactions into measurable optical signal changes, thus achieving labelfree, realtime detection of biomarkers. Configurations based on interferometry, fiber Bragg gratings (FBGs), Dshaped fibers and microstructured fibers have been widely used for detection of cancer markers, viruses, bacteria, and hormones.

In the context of spectral analysis in biochemical analysers, midinfrared fluoride fibers demonstrate unique advantages. The midinfrared band covers the molecular fingerprint region and atmospheric transmission windows, making it one of the most critical wavelength ranges for sensing and spectral analysis. Fluoride fibers (represented by ZBLAN) offer a broad transmission window and low phonon energy, overcoming the transmission loss bottleneck of conventional silica fibers at long wavelengths, thereby providing an ideal fiber platform for highsensitivity trace substance detection. Currently, midinfrared fluoride fibers have been successfully used in gas sensing, biological diagnostics and environmental monitoring, and their spectral analysis capability is expected to play an important role in the miniaturisation and integration of biochemical analysers.

In addition, hollowcore antiresonant fibers (HCARFs) as an emerging sensing platform also show promising prospects for labelfree molecular sensing. By introducing the sample into the hollow core, the lightmatter interaction length can be greatly enhanced, significantly improving detection sensitivity. With continued development of fiber grating sensing technology and surface plasmon resonance (SPR) enhancement, fiber-optic biosensors are moving towards multitarget simultaneous detection and deep integration with artificial intelligence algorithms, meeting the needs of personalised medicine and intelligent diagnostic systems.

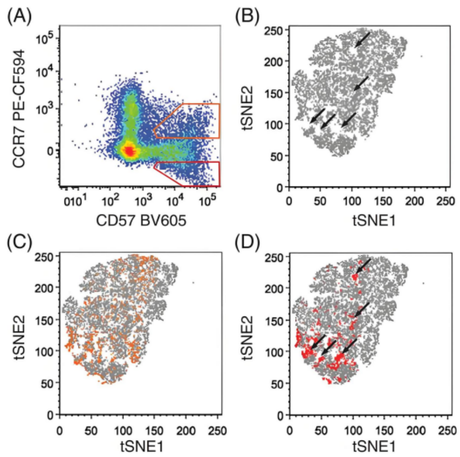

Figure 1. Flow cytometry analysis of cellular biomarkers.

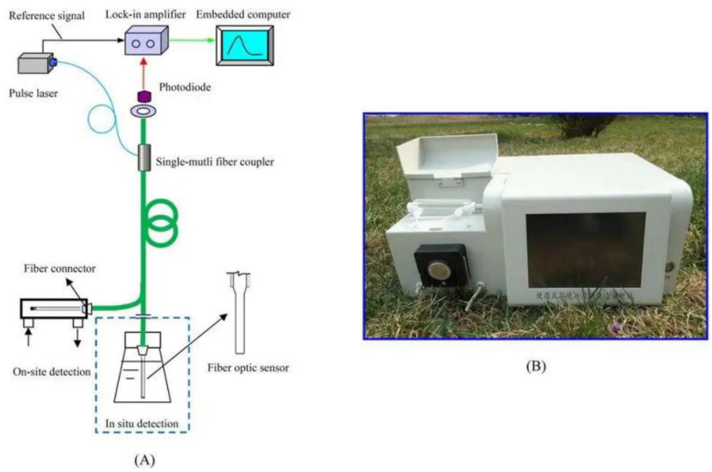

Figure 2. Schematic of evanescent-wave all-fiber biosensing platform and detection principle.

2.2. Holmium laser lithotripsy and novel fiber lasers

Urolithiasis has a high global incidence, and laser lithotripsy has become the standard method for treating upper urinary tract calculi. For a long time, the Ho: YAG laser, with its excellent water absorption characteristics and efficient photothermal effect, has been recognised as the gold standard for laser lithotripsy. However, clinical applications of Ho:YAG laser still have shortcomings such as stone retropulsion, risk of thermal injury, and difficulties in accessing lower pole calyces.

In recent years, the emergence of thulium fiber lasers (TFL) is profoundly changing this landscape. TFL offers better electrooptical conversion efficiency, more stable output power, and smaller fiber diameter,

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enabling higher peak power within shorter pulse widths, thereby producing finer dusting fragmentation and less stone retropulsion. A systematic review published in 2025 included 8 studies (involving more than 1,000 patients) systematically comparing TFL with pulsemodulated Ho: YAG laser in ureteroscopic lithotripsy, retrograde intrarenal surgery, and minipercutaneous nephrolithotomy. The results showed that TFL achieved stonefree rates comparable to or slightly better than Ho: YAG (82–98% for TFL vs. 56–95% for Ho: YAG), with less retropulsion, better endoscopic visualisation, and equivalent safety. With higher ablation speed, lower retropulsion and better compatibility with thin fibers, TFL is increasingly becoming the preferred nextgeneration laser lithotripsy platform.

It is worth noting that the above lithotripsy performance relies heavily on the transmission properties of specialty optical fibers. TFL operates around 1.94 μm, which is near the strong water absorption peak, posing high demands on the optical damage threshold and transmission efficiency of the fiber. Continuous improvements in midinfrared fluoride fibers and specialty silica fibers provide solid technical support for stable TFL operation at high repetition rates.

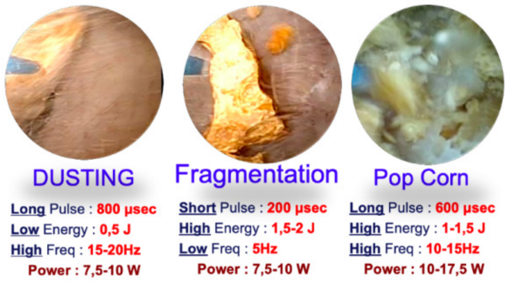

Figure 3. Schematic illustration of holmium laser lithotripsy.

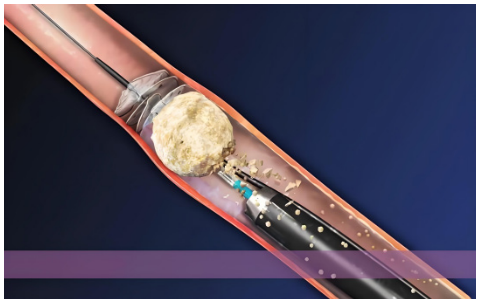

Figure 4. Schematic of minimally invasive percutaneous nephrolithotomy procedure.

2.3. Endovenous laser ablation for varicose veins

Varicose veins have a high incidence in chronic venous insufficiency, and thermal ablation techniques have been recommended as the firstline minimally invasive treatment in recent clinical guidelines. Endovenous laser ablation (EVLA) delivers laser energy precisely to the diseased venous intima via an optical fiber, inducing thermal injury and fibrotic closure of the venous wall, thereby achieving a cure. In the early 2000s, EVLA mainly used nearinfrared diode lasers at 800–980 nm, offering deep thermal penetration but accompanied by higher tissue collateral damage risk.

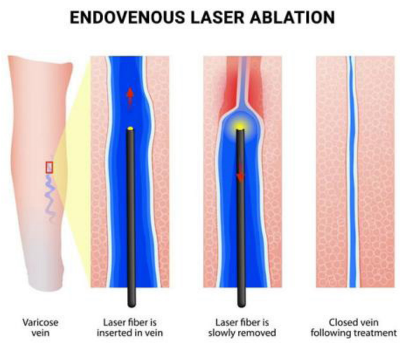

Figure 5. Schematic diagram of endovenous laser ablation (EVLA) procedure.

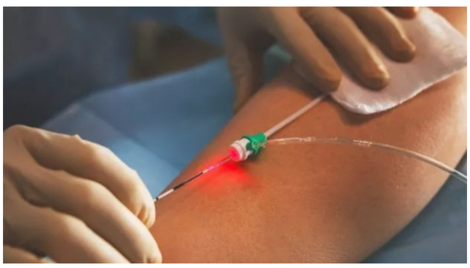

Figure 6. Clinical illustration of endovenous laser ablation procedure.

Recently, lasers with wavelengths >1900 nm have been introduced into EVLA. A 2024 multicentre clinical study reported the use of a 1940 nm laser diode combined with a novel cylindrical singlering optical fiber for treating lowerlimb venous insufficiency. The study included 93 patients and 100 procedures. The target vein closure rate at 7 and 30 days postprocedure was 100%, and remained at 99%, 96.9%, and 95.9% at 6month, 1year, and 2year followup, respectively. The pain visual analogue scale scores at 1 and 7 days after the procedure were only 2 and 1, and all patients experienced clinical symptom improvement. These results indicate that using a laser with wavelength >1900 nm together with a circumferentially emitting fiber can achieve high closure rates while significantly reducing energy delivery parameters and postoperative pain. In this interventional setting, the fiber is not only an energy carrier – the geometric design of the fiber tip (e.g., ring fiber, radial emitting fiber) and the precise combination of laser wavelength and pulse parameters jointly determine the therapeutic effect and safety margin.

2.4. ELCA: Excimer laser coronary atherectomy

In the field of cardiovascular intervention, excimer laser coronary atherectomy (ELCA) is one of the most technically distinctive clinical applications of specialty optical fibers. ELCA uses a 308 nm ultraviolet xenonchlorine excimer laser, delivering highenergy ultraviolet pulses through a flexible fiber optic catheter to the coronary plaque site. The lasertissue interaction involves a synergistic combination of photochemical bond cleavage, photothermal vaporisation, and photomechanical stress waves, gently ablating complex lesions including atherosclerotic plaques, fibrous tissue, moderately to severely calcified lesions, and thrombi, while causing minimal thermal damage to the surrounding normal vessel wall.

ELCA is currently widely used in scenarios such as stent underexpansion, moderatetosevere calcification, saphenous vein graft disease, and acute myocardial infarction. In these applications, the performance design of the fiber catheter is critical – the light transmission efficiency, bend resistance, core diameter distribution, and manoeuvrability within narrow coronary vessels directly determine the accuracy and safety of laser ablation. With the help of computer simulation, researchers can now systematically analyse the quantitative influence of design parameters such as the helix angle, number of fiber cores, and core diameter on the mechanical properties and spatial distribution of laser output, providing a theoretical basis for the optimisation of nextgeneration ELCA fiber catheters.

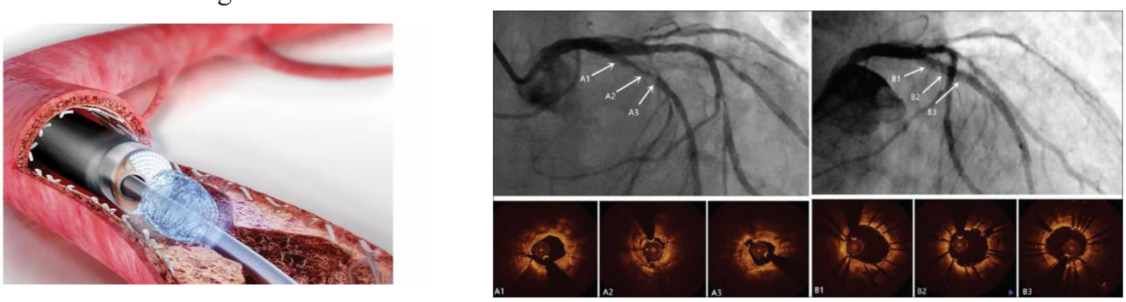

Figure 7. Mechanism and clinical application of excimer laser coronary atherectomy (ELCA).

3. Industrial applications of specialty optical fibers

Industrial applications of specialty optical fibers also follow three parallel tracks: Precision measurement, power system structural monitoring, and underwater acoustic detection. Although the technical principles differ, these applications share a common feature – fully exploiting the distributed sensing capability and harshenvironment adaptability of optical fibers.

3.1. Fiber-optic ranging technology

Fiber-optic ranging is one of the most widely used directions of fiber-optic sensing in industrial measurement. The basic principle is to achieve highresolution distance or deformation detection by precisely measuring the propagation time of light in the fiber. In distributed fiber-optic sensing systems, schemes based on Brillouin optical timedomain reflectometry (BOTDR) and phasesensitive optical timedomain reflectometry (ΦOTDR) enable continuous temperature and strain monitoring over the entire fiber length, with spatial resolution down to the metre or even centimetre level. This distributed measurement capability holds great promise for largescale industrial infrastructure such as bridge structural

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health monitoring, dam settlement observation, and oil/gas pipeline deformation monitoring.

In recent years, with the development of femtosecond laser direct writing, optical frequency domain reflectometry (OFDR), and highsensitivity interferometric detection methods, the measurement accuracy and dynamic response capability of fiber-optic ranging systems have been greatly improved. Particularly in highend manufacturing fields such as deepsea exploration, aerospace pose measurement, and precision equipment assembly alignment, micrometrelevel highprecision ranging based on FBG and interferometric sensors is gradually moving from laboratory research to engineering applications.

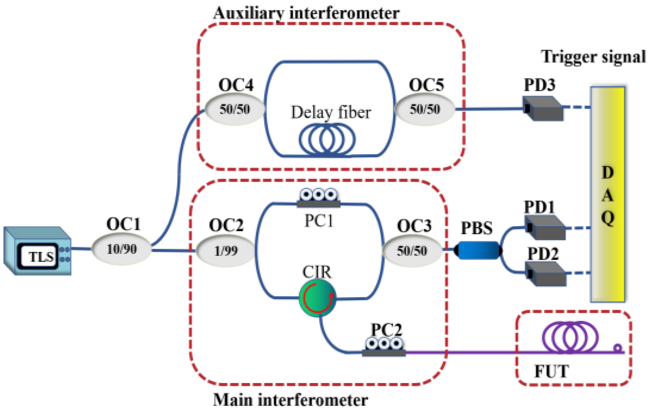

Figure 8. Optical frequency domain reflectometry (OFDR) sensing technique.

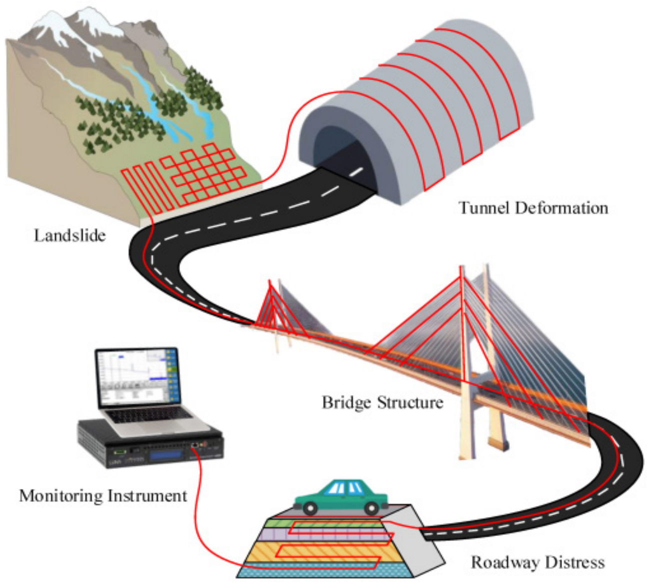

Figure 9. Schematic of distributed fiber-optic sensing system.

3.2. Optical fiber composite overhead ground wire and converter valve temperature monitoring

The construction of smart grids demands higher standards for condition awareness of highvoltage transmission lines and key equipment in converter stations. Optical fibre composite overhead ground wire (OPGW) embeds specialty optical fibers into the conventional overhead ground wire structure, serving both lightning protection and optical communication functions, and has become one of the fundamental infrastructures of smart grids. Building on this, the integrated fibers in OPGW can also be used as distributed temperature and strain sensors. Using BOTDR technology, the temperature distribution along the transmission line, tower tilt, and fiber strain can be monitored in real time, providing key data for line icing monitoring, deicing control and line creep early warning.

In ultrahigh voltage direct current transmission systems, the operating temperature of converter valves – the core equipment for AC/DC conversion – directly affects system stability and equipment lifetime. The thyristors and heat sinks in converter valves accumulate heat significantly under longterm high load. Undetected abnormal temperature rise can cause converter valve failure or even converter station

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shutdown, leading to severe economic losses and grid safety hazards. Fiber-optic temperature measurement systems offer unique technical advantages here – the fibers are nonconductive, immune to electromagnetic interference, and withstand high voltages, allowing safe deployment in the highvoltage insulation environment of converter valves. Currently, temperature monitoring solutions based on fluorescence fiber sensing and FBG arrays have been successfully applied in many converter stations in China, enabling realtime online measurement of thyristor junction temperature and water cooling system inlet/outlet temperatures. These systems not only continuously collect distributed temperature data but also provide a sensing basis for fault early warning and load optimisation scheduling, effectively supporting the intelligent operation and maintenance of HVDC transmission systems.

At the same time, research on partial discharge detection based on distributed acoustic sensing (DAS) in highvoltage cables and gasinsulated switchgear of converter stations has also made positive progress. By winding a multimode optical fiber around cable terminals or GIS bushings, DAS systems can detect ultrasonic vibrations caused by insulation defects; laboratory detection sensitivity reaches around 40 pC, with simultaneous localisation of different discharge sources. Although the dynamic range and detection reliability of this technique still lag behind traditional PD detection methods, its nonintrusive, largescale deployable nature gives it unique potential for substationwide PD monitoring.

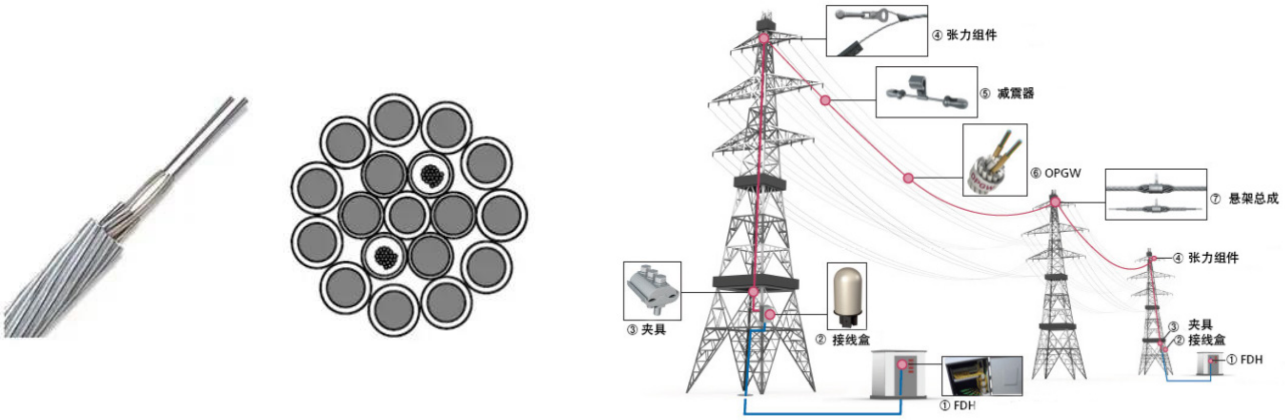

Figure 10. Structure and application of optical fiber composite overhead ground wire (OPGW).

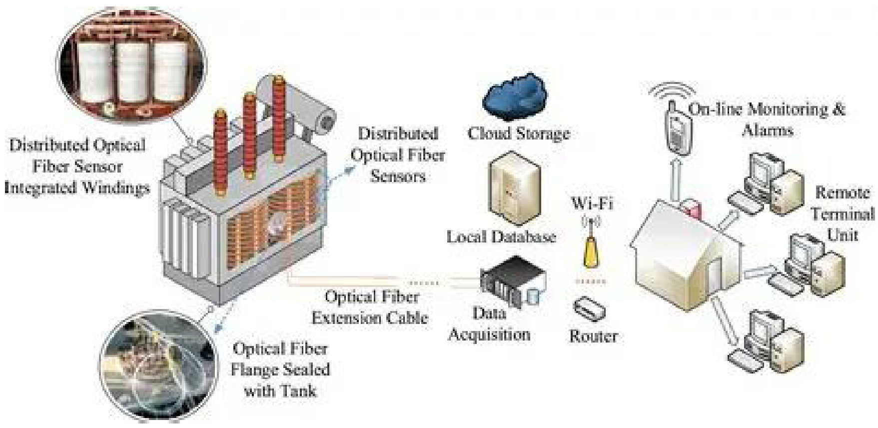

Figure 11. Real-time temperature monitoring of HVDC converter valves using fiber-optic sensing.

3.3. Distributed fiber-optic hydrophone technology

Underwater acoustic detection is a key technology in marine sensing, with extensive application requirements in marine target detection, communication navigation, resource exploration, and marine ecological monitoring. Traditional hydrophones mainly include piezoelectric types and interferometric fiber-optic hydrophones (FOH). The former are technologically mature but have fixed array element scales; the latter have high sensitivity but still belong to "nodetype" arrays – their wetend fabrication relies on manual operations and complex array weaving, making them difficult to satisfy largescale marine acoustic monitoring needs.

Distributed fiber-optic hydrophone (DFOH) technology is a revolutionary innovation in underwater acoustic detection. Its core innovation is to transform an entire ordinary singlemode optical fiber into thousands of continuously distributed acoustic transducers through optical phase demodulation, using the phase difference of backscattered signals from laser pulses propagating along the fiber to reconstruct the spatiotemporal distribution of the external acoustic field. Compared with conventional hydrophones, DFOH brings several fundamental changes:

Spatially continuous sensing – no physical gaps between sensing channels, fundamentally overcoming the spatial undersampling problem of conventional nodetype arrays;

Flexibly reconfigurable array – the spacing, aperture and subarray composition of the hydrophone array are all adjusted digitally via signal processing, adaptively matching the spectral characteristics of the target;

Fully automated wetend fabrication – no discrete fiber components or manual weaving; the entire wetend can be drawn in one continuous process, dramatically improving array consistency and production efficiency;

Kilometrescale largearray capability – sensing distances can extend to tens of kilometres, with total array elements reaching thousandpoint levels, suitable for largearea marine acoustic monitoring.

A review published by the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, indicates that DFOH systems have been demonstrated in fields such as underwater target detection, tsunami early warning, and marine seismic monitoring. Compared with conventional piezoelectric or interferometric technologies, DFOH achieves thousandpoint acoustic sensing with a single ordinary fiber, laying the technical foundation for largescale, lowcost intelligent underwater acoustic monitoring networks.

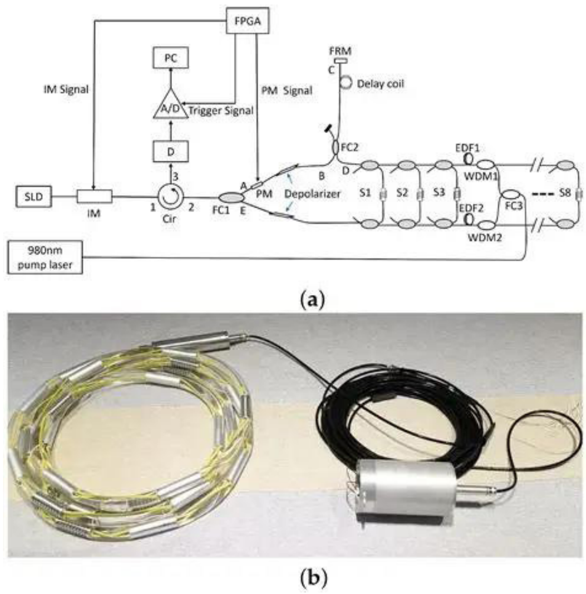

Figure 12. Distributed fiber-optic hydrophone sensing principle.

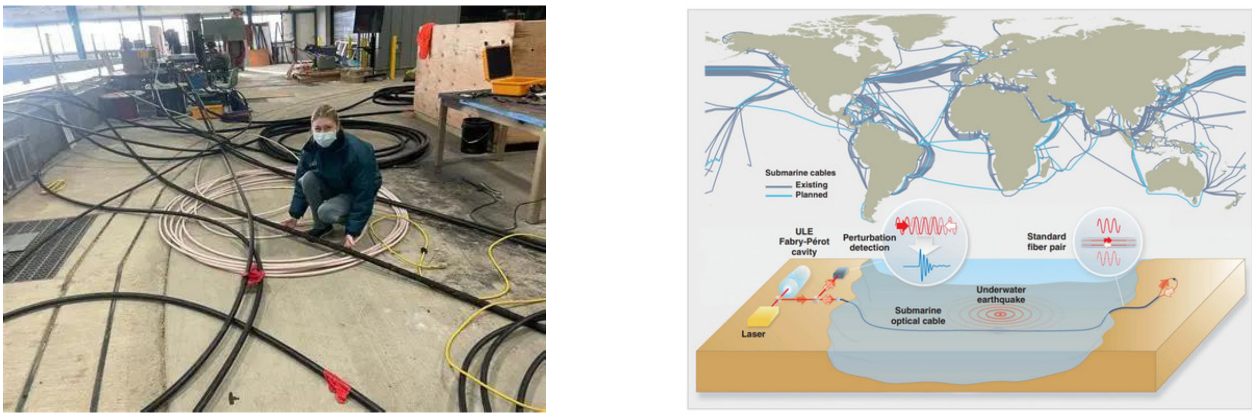

Figure 13. Applications of fiber-optic sensing in marine monitoring systems.

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4. Future technical challenges and trends

Although crossdisciplinary applications of specialty optical fibers have formed two main lines – medical and industrial – each direction still faces significant common technical bottlenecks and differentiated challenges.

(1) Multimaterial fibers and multifunctional integration. As application scenarios demand that a single fiber function go from "transmission" to multicompound "sensing + actuation + regulation", how to precisely integrate dissimilar materials such as optoelectronic conversion materials, piezoelectric materials, thermoelectric materials, and biofunctional materials into a submillimetrescale fiber is the most important frontier. The thermaldrawbased multimaterial fiber fabrication technology has made significant progress; researchers have successfully integrated conductive metals, semiconductors, and piezoelectric materials in polymer fibers, achieving singlefiber multiparameter (optical, electrical, acoustic) detection simultaneously. However, thermomechanical matching of multimaterial interfaces, material compatibility, and scalable fabrication remain unavoidable bottlenecks.

(2) Nanoscale light manipulation and metafibers. A 2025 review summarised the paradigm shift of metafibers: The deep integration of the extraordinary lightmanipulation capability of metasurfaces with mature fiber platforms is opening entirely new technological pathways for structured light generation, precision imaging, and highsensitivity sensing. In the future, specialty fibers with metafunctional elements are expected to achieve breakthrough performances such as arbitrary infiber optical field modulation, beam shaping, and subwavelength resolution sensing.

(3) AI and intelligent fiber systems. Artificial intelligence is entering the realm of specialty fiber signal processing and system optimisation. Whether for intelligent decoupling of multiparameter spectral signals in biochemical sensors or for pattern recognition and noise suppression of target signals in distributed fiber-optic hydrophones, the integration of AI algorithms is opening new avenues for improving system detection sensitivity and reducing deployment costs. It is foreseeable that with the positive interaction between specialty fibers and machine learning methods, "intelligent fiber sensing systems" are gradually moving from concept to preliminary engineering realisation.

5. Conclusion

The development of specialty optical fiber technology is profoundly reshaping engineering practices in the medical and industrial sectors. From optical fiber catheters that precisely deliver laser energy in medical interventions, to online sensing of converter valve temperature and partial discharge in power systems, and to distributed fiber-optic hydrophones capable of kilometrescale underwater acoustic monitoring, specialty optical fibers – thanks to their unique electromagnetic immunity, electrical insulation, distributed sensing capability, and material adaptability – are becoming multifunctional smart carriers supporting modern technological progress. The crossintegration of multimaterial fiber integration, metafiber structural design, and AIempowered sensing technology will further expand the boundaries of specialty optical fibers, potentially elevating them from an "enabling technology" to an indispensable "core infrastructure" in numerous strategically important industrial innovation systems.

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