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Development Trend of Laser Technology Application in the Information Field Toward 2035

Research Group of *Strategic Research on China's Laser Technology and Its Application in Information by 2035*

Abstract: Laser technology has been widely used in the field of information since it was invented and has promoted the rapid development of information technology, which has become the main driving force for the development of information technology. "Strategic Research on China's Laser Technology and Its Application in Information by 2035" is a key sub-project of the major consulting project "Strategic Research on China's Laser Technology and Its Application by 2035" launched by the Chinese Academy of Engineering. It aims to conduct a comprehensive research on the application of laser technology in the information field and on the development of related industries in China, analyze the development trend of laser technology in the information field, and propose suggestions to promote the development of the field. This paper introduces the major application of several laser technologies—optical communication, laser display, optical storage, and optical sensing—in the information field, and analyzes the research and development status of laser technology, the major key technologies, and the development of related industries in China and abroad. To promote laser technology application in the information field, we suggest that China should establish key research directions and promote the development of core technologies, build an industrial innovation platform to improve technological innovation, lay emphasis on intellectual property protection, and strengthen the training of high-end talents; guide the cooperation of government, industry, education, and research to promote achievement transformation; increase policy support and guide the healthy development of the industry; exploit the advantages of industrial agglomeration to enhance the competitiveness of enterprises.
Keywords: laser technology; optical communication; laser display; optical storage; optical sensing

1 Introduction

Invented in 1960, the laser is a remarkable invention of the 20th century with application in fields such as atomic energy, computer science, and semiconductor technology. Compared with conventional light sources, laser sources have the advantages of good monochromaticity, strong coherence, high brightness, and good directivity. They can be adopted in industrial and agricultural production, communication, medical treatment, scientific research, and national defense. The development of lasers has initiated a significant revolution in optics, enhanced the advancement of information technology, and ushered in the information age [1]. In particular, the advent of semiconductor lasers has directly contributed to the application of laser technology in fiber-optic communication and enabled the progression of communication technology from the electronic era to the optoelectronic era.

Currently, the rapid development of laser technology has infiltrated every field of information technology. As the extension and development of electronic information technology, lasers have become the main driving forces for the development of information technology. The applications of laser technology in the information field include laser imaging, ranging, sensing, detection, communication, information processing, display, and storage. It has also made significant contributions to the promotion of national informatization, national defense, construction, aerospace,

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energy, environment, and other important strategic security fields. Furthermore, it has provided unprecedented channels and opportunities for scientific exploration as well as scientific and technological innovation.

Particularly, laser technology and industrial development in the information field are at the forefront of China's strategic goals in becoming an innovation-oriented country. Although China has achieved significant progress in laser information technology after decades of development, there is a wide gap between the development and industrialization of basic components in China and those of advanced countries. Owing to fierce international competition, it is necessary to seize the strategic opportunity of international scientific and economic developments to adjust China's economic structure in order to accelerate the development of laser information technology and industrial capacity.

2 Application of laser technology in the information field

The wide application of laser technology in the information field has ushered in the information age. Laser technology is mostly adopted in optical communication, laser displays, optical storage, and optical sensing.

2.1 Optical communication technology

Modern communication technologies that rely heavily on lasers are principal applications of laser technology. These communication technologies are divided into fiber-optic communication and wireless laser communication based on the transmission medium. Optical communication is a communication mode that uses laser as a carrier to transmit information such as voice, image, and data. It has the advantages of high speed, large capacity, and strong anti-interference.

2.1.1 Fiber-optic communication

Fiber-optic communication uses lasers as carriers and optical fibers as the conducting medium to transmit information. It has been used in communication systems for over 40 years. Owing to its faster transmission speed, lower energy loss, and higher laser modulation rate, fiber-optic communication can improve communication performance compared with traditional systems, and it has significant economic value and unlimited industrial prospects [2]. Technological advancements such as the development of low-loss optical fiber and the semiconductor laser invented in 1976 by a Chinese scientist, Charles K. Kao, has led to the commercialization of fiber-optic communication. Five-generation technologies include laser carriers from 0.85 μm, 1.31 μm, and 1.55 μm wavelength-division multiplexing. Additionally, coherent communication technology has been developed. Following the improvements in laser performance, single-channel 400 Gb/s commercial equipment have become operational.

Owing to the increase in optical fiber communication bandwidth, the United States Department of Defense established a network in the 1960s, which has now become the current global Internet and an information highway. Particularly, in the last 20 years, fiber-optic communication technology has continuously enhanced network capacity (reaching dozens of TB/s), thereby enabling an increase in the total number of mobile communication bandwidths and service users. Thus, it is a fast-growing field. Fiber-optic communication is considered as a significant technological achievement of the 20th century, and it is a fundamental technology for progress into the information age. Moreover, it facilitates global information exchange and accelerates economic globalization. It has also transformed the economic model used for centuries and rapidly improved the quality of human life.

China has witnessed rapid progress in fiber-optic communication technology and the information industry [3]. In addition to China's advancement in the research and development (R&D) of optical communication equipment and systems, its engineering application capabilities have reached excellent levels. Some Chinese communication enterprises, such as Huawei Technologies Co., Ltd., ZTE Corporation, YOFC, and FiberHome Telecommunication Technologies Co., Ltd., have become top-ranking high-tech enterprises in their respective fields. Currently, China ranks first in the world in terms of production capacity and market shares. Its output and market share of optoelectronic devices such as communication lasers is about half of the global market, and its market share of optical transmission equipment exceeds one-third of the global market. With regards to technology, it is second only to the United States and Japan [4].

2.1.2 Wireless laser communication

Laser communication combines the advantages of radio and fiber-optic communication, along with strong anti-interference and anti-interception abilities, good security, high communication rate, high speed, and large

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information capacity. It also has a small volume, light weight, low power consumption, simple construction, and flexible mobility, and it has a significant demand and wide application in military and civilian fields [5,6].

In the 1970s, the United States, Europe, Japan, Russia, and other countries conducted a series of studies on wireless laser communication for space-based, atmospheric, and underwater channels. Through several years of research and experimental verifications, laser satellite communication has been shown to have significant advantages compared with microwave satellite communication. In 2008, the German Aerospace Center used the TESAT satellite to perform an interplanetary 45 000-km on-orbit laser communication test at a rate of 5.625 Gb/s with a 1.06-μm laser carrier. In October 2013, the National Aeronautics and Space Administration tested a 400 000-km laser transmission between the moon and the Earth, with maximum downlink and uplink speeds of 622 Mb/s and 20 Mb/s, respectively [7,8].

In the 1970s, China began research on atmospheric laser communication technology and launched a project on space laser communication in the 1990s, a feat that rapidly placed China on par with advanced countries. In 2007, the Changchun University of Science and Technology initiated advancements in the technology of capturing, aligning, and tracking long-range beams, and achieved the first dual-dynamic laser communication. In 2013, it tested the first long-range laser communication between two fixed-wing aircrafts in China at a rate of 2.5 Gb/s. The transmission distance of 144 km exceeded the international longest distance in a similar experiment. Moreover, in 2011, the Harbin Institute of Technology conducted China’s first satellite-to-ground laser link data transmission experiment with a maximum downlink speed of 504 Mb/s. In 2017, the first satellite-to-ground high-speed coherent laser communication technology experiment was performed by the Shanghai Institute of Optics and Mechanical Engineering, Chinese Academy of Sciences, with a maximum downlink speed of 5.12 Gb/s. Furthermore, the world’s first high-orbit satellite-to-ground high-speed laser two-way communication experiment was performed with the Shijian-13 high-flux satellite and a satellite-to-ground laser communication terminal in China. The maximum speed of the satellite-to-ground communication was 5 Gb/s at a distance of 40 000 km.

Wireless laser communication technology has witnessed significant developments and has been extended to underwater, atmospheric, and indoor visible light communication. Following advancements in science and technology and the demand for information, wireless laser communication technology will become the principal transmission technology in the communication field to promote the development of the Internet of Things and intelligent networks and probably improve production activities, life, and the societal cultures.

2.2 Laser display technology

Laser display is the fourth generation of display technology after black-and-white displays, color displays, and digital displays. It is a product of the rapid development of laser, optoelectronic, and semiconductor technologies. Following the advancements in laser technology, laser display advances the 12-bit gray-scale coding without overlapping, has high brightness, and can be controlled in the best visual perception area of the human eye to achieve 8 K geometric HD. Tri-primary LD laser display technology is the only display technology that can fully implement the BT. Because lasers have good directivity, good monochromaticity, and high brightness, they can achieve a large color gamut, double HD (geometry, color) video image display, and true 3D display. They are considered an optimal method for achieving high-fidelity image reproduction and are a suitable direction for the development of new displays [9].

Laser display technology has witnessed rapid developments in China. Supported by the 863 Program, Xu Zuyan of the Institute of Physics and Chemistry, Chinese Academy of Sciences developed the first prototype of a laser panchromatic projection display (all-solid-state laser source) in China in 2005. In 2015, the first international 100-inch three primary color LD laser TV prototype was developed, which indicated the feasibility of the industrialization of laser display technology. In the 13th Five-Year Plan, laser display was listed as the first item of new information technology. Previously, China granted more than 7000 laser display patents, accounting for over 50% of global laser display patents. Moreover, it was the convener of the IEC-TC110 laser display working group, leading and participating in the formulation of several IEC standards [10].

Although the power, efficiency, and reliability of China’s domestic trichromatic LD significantly lag behind those of other countries, the trichromatic LD laser display technology has entered a rapid development stage, and significant advancements are expected shortly.

2.3 Optical storage technology

With the dissemination of all kinds of information, the daily management of the information capacity (in TB) and information flow (in TB/s) is required. After the invention of lasers, optical storage technology was developed, and the use of laser light sources has overturned the concept of capacity for magnetic storage technology. Optical storages adopt non-contact reading, writing, and wiping modes that cause little damage to the disk surface. They also have long storage life and stable storage medium as data can be maintained for more than 10 years with good mobility and low cost. Optical storage is the most efficient and the largest storage technology that has been widely used for a long period and will continue being used in the future. Following the demands of big data, cloud computing, the Internet of Things, and artificial intelligence, ultra-large capacity optical storage technology has been rapidly developed, and its capacity has surpassed that of Tbit. Meanwhile, several optical storage technologies, such as volume holographic storage, near-field optical storage, and two-photon bistable storage, have been developed. Holographic storage uses laser holography technology to achieve three-dimensional image storage with a larger storage capacity [11].

Domestic optical storage technology has developed three generations. Most technologies have mastered independent intellectual property rights, with the fourth or fifth generation of optical storage technology conditions, strength, and capacity. Optical storage is now breaking the diffraction limit and develops toward ultra-high-density information storage direction, and from two-dimensional to multi-dimensional storage. Thus, new high-capacity optical storage technology has been rapidly developed. Blue-light storage technology has also been industrialized and continuously expanded in scale, and two-beam super-resolution and glass storage technologies have entered the engineering and industrialization stages. Furthermore, multi-wavelength and multi-order optical storage and holographic storage are steadily advancing, as well as research on fluorescent nanocrystal storage, DNA storage, and near-field optical storage. In 2019, the storage capacity of a single optical disk reached 500 GB owing to the improvements in laser performance and storage technology.

2.4 Optical sensing technology

Optical sensing technology is similar to optical communication technology because it uses light as a carrier to sense and transmit external measured signals. From the perspective of large-scale applications, optical sensing technology is mainly divided into LiDAR and optical fiber sensing.

2.4.1 LiDAR

LiDAR technology has been used for environmental sensing and ranging since the first laser was invented in 1960. The first laser rangefinder was introduced in the United States Army in 1961. Compared with conventional radar technologies such as millimeter wave, microwave, and ultrasonic radar, LiDAR can significantly improve the range, angle, and velocity resolution of radar. The high directivity and coherence of lasers enable long-range and anti-interference detection [12]. Beginning with its military applications, LiDAR has rapidly evolved into an advanced active remote sensing tool. Single-point ranging, single-channel scanning imaging, multi-channel scanning imaging, planar array imaging, etc. have been developed, and LiDAR has developed from single-channel two-dimensional scanning imaging radar to fringe-tube staring imaging radar and gate-gated range imaging LiDAR.

For atmospheric monitoring, differential absorption LiDAR can measure water vapor, ozone, atmospheric pollutant levels, etc. Backscatter LiDAR can detect the particulate concentrations and spatial distributions of atmospheric aerosols. Meanwhile, doppler LiDAR measures wind speed, wind shear, and dust storms. LiDAR can also detect ocean depths, reefs, fish shoals, shipwrecks, precious resources such as plankton, and chlorophyll concentrations that are difficult to identify in the deep ocean. Furthermore, it uses Raman scattering to measure ocean subsurface temperatures; Brillouin scattering to measure temperature, speed of sound, and salinity in the ocean; and the fluorescence effect to measure oil and gas escape from the surface owing to accidents. LiDAR is used for reconnaissance imaging, obstacle avoidance, chemical agent detection, mine detection, and weapon guidance. It can be used for the three-dimensional mapping of targets as well as the rendezvous and docking of spacecraft. Additionally, LiDAR technology is a principal technology in the field of unmanned driving, and it will alter human activities in the future.

Important LiDAR technologies include laser transmitter technology, space scanning technology, high-sensitivity receiver design technology, and terminal information processing technology. LiDAR relies on the performance of lasers (laser transmitters), and it is divided into ultraviolet, visible, and infrared LiDAR based on the laser band, and gas, solid, and laser diode LiDAR based on the laser medium. Based on the transmitting waveform, it can be divided

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into pulse, continuous wave, and hybrid LiDAR. The technical development of lasers directly determines the technical progress and application popularization of LiDAR. Following the development of new technologies such as fiber lasers and quantum cascade lasers, the performance of lasers has improved in terms of tunable band expansion, line width, energy, and pulse. This will enable LiDAR to achieve higher measurement accuracy and better practicality.

2.4.2 Optical fiber sensing

Similar to fiber-optic communication technology, optical fiber sensing technology uses a laser source as a sensing signal, optical fibers and optical fiber devices as sensors. It obtains sensing information through the demodulation of the sensing laser. It is free from electromagnetic interference, has a small size, is distributed, is easy to integrate, has a high measurement accuracy, and can form a self-organizing network.

In practical applications, all sensors are often composed of an optical fiber sensor network that measures several signals. Thus, laser sources such as quantum cascade lasers, laser diodes, light-emitting diodes, Brillouin fiber lasers, and Raman fiber amplifiers are often used as sensing sources. The measurement of temperature, pressure, flow, displacement, vibration, rotation, bending, liquid level, velocity, acceleration, sound field, current, voltage, magnetic field, and radiation [13] are widely used in military, national defense, aerospace, industrial and mining enterprises, energy, environmental protection, industrial control, medicine and health, measurement and testing, construction, household appliances, and other fields.

Optical fiber sensing technology can perform important roles in large-scale construction projects. In 1993, Canada preinstalled fiber-optic sensors on a carbon fiber prestressed concrete bridge and used dynamic planning theory to process data to rapidly and accurately evaluate the bridge's service life. In the construction of the Three Gorges Project in China, fiber Bragg grating temperature sensors installed in the dam near the upstream face have higher accuracy than direct water temperature measurements with mercury-in-glass thermometer. Currently, optical fiber array sensing systems that can achieve large-range, long-distance multi-point sensing, combined with distributed optical fiber sensing systems, have been widely used. They have become an important development trend of large-scale optical fiber sensing and distributed monitoring systems for large infrastructure projects, such as the National Stadium in Beijing, the Guangzhou TV Tower, and high-speed rail lines, which use fiber-optic array sensing technology. Modern infrastructure and industries such as energy increasingly adopt fiber-optic sensing technology.

3 Prospects for development trends for 2035

3.1 Optical communication technology

Currently, China's fiber-optic communication has advanced the 100 Tb/s@80 km transmission technology to ultra-high speed, ultra-large capacity, and ultra-long distance [14]. By 2025, 100 Tb/s ultra-high-speed fiber-optic communication system is expected to be achieved, and key electronic, photonic, and optoelectronic device integration applications for front-end communications will be fully achieved by 2035, which will exceed 1000 Tb/s high-speed optical fiber information transmission. The future of fiber-optic communication technology will bring significant benefits to mankind, and it will be a significant factor for China to achieve the "two centenary goals."

Although wireless optical communication can achieve Tb/s-level transmission through new technologies such as orbital angular momentum multiplexing, the transmission distance is limited and long-distance transmission beyond 10 Gb/s is difficult. With the development of light sources, amplifiers, and detection systems, 40 Gb/s space high-speed laser long-distance transmission can be achieved by 2025 and used in space communication. By fully integrating key electronics, photons, and optoelectronic devices at the front end of the fiber-optic communication in 2035, space laser communications can exceed 100–400 Gb/s high-speed transmission and be applied in fields such as space information network, deep space communication, broadband access, and underwater exploration.

3.2 Laser display technology

In the field of display, the overall trend toward high-definition, high-color-saturation laser two-bit and three-dimensional display technology, including laser holographic display technology, micro-LED display technology, flexible display technology requires the system to be smaller with higher resolution and wider color gamut. In 2022, China will achieve ultra-high-definition video, 4 K/8 K ultra-high resolution display chip, ultra-high-definition video image acquisition/storage/processing/transmission, human-eye biological characteristics, visual psychological characteristics, and other key technologies. The maximum output power of three primary color LD light sources such as red LD single tube, blue LD single tube, and green LD will be up to 2 W (service life over 10 000 h), 2.8 W (service life over 5 000 h), and 500 mW, respectively, thereby reaching practical levels and solving the problem of dependence on imports. The overall development target by 2025 is ultra-high-definition and head-mounted bespectacled 3D display technology, which will achieve naked-eye 3D display technology.

3.3 Optical storage technology

Individual technologies and system integrations related to optical storage can be stabilized by 2022, with the purchase cost of storage reaching 1 cent/GB [15]. Recently, the performance of ultrafast lasers, such as femtosecond lasers, has rapidly improved, thereby leading to advances in new storage technologies. These storage technologies with high storage capacity, density, reliability, and data transfer rate will enable ultra-large capacity, ultra-high efficiency, ultra-high throughput, low cost, and wide compatibility of optical storage products. The corresponding industry, national, and international standards will be significantly perfected and popularized in all areas. Furthermore, terabytes of optical disk storage will be achieved by 2025, and petabytes of the optical disk storage system will be advanced by 2035.

3.4 Optical sensing technology

With the development of LiDAR toward high sensitivity, high signal-to-noise ratio, high resolution, and wide measurement range, the performance of the sensing front end is developing toward integration, multi-parameter, and multi-functioning. By 2025, LiDAR will be completely used in intelligent networks, unmanned driving, and other fields, and it will be the principal growth force of unmanned driving. Furthermore, it will advance 3D radar imaging. By 2035, driverless cars will be important components of driving because of the increase in smart cars, and intelligent LiDAR technology will be the principal device in the fields of land, water, aviation, and unmanned driving.

Owing to the development of advanced laser technologies such as narrow linewidth lasers, the technology of intelligent optical fiber sensor networks will become mature and perform significant roles in several fields. It will also enhance China’s independent innovation capacity, the international competitiveness of China’s information industry, and the rapid and sustainable development of the national economy. By 2025, ultra-high resolution and ultrafast optical fiber sensing technology is expected to be achieved. By 2035, distributed intelligent optical sensing systems will be applied in the ultra-distant fields of ocean, earth center, and space, and become the most important infrastructure of the wide-area Internet of Things.

4 Policy recommendations

Currently, the application of laser to China’s information industry is in the period of extensive development. Hence, several opportunities and challenges coexist. Owing to the severity of the current international political and economic situation, the information industry and the development of laser technology will meet external constraints. Because of the universal significance of laser technology in livelihood, industry, and military, the following recommendations are proposed to promote the application of laser technology to China’s information industry to enable it to reach the leading position in the world by 2035.

4.1 Establishing research directions and focus and developing core technologies

Based on the current industrial development of laser technology in China and its application to information technology, the key technology challenges that need to be solved in the development, industrial, and large-scale application of laser information technology should be analyzed. According to the degree of priority, we will establish a research direction that will lead to key breakthroughs and form a targeted layout through various science and technology plans at the national level. This will fully enable the guiding role of the national science and technology plans and strengthen the supporting policies for technological innovation. Furthermore, we will improve the mechanisms for collaborative innovation between industry, university, research, and application; rely on the strength of industry, university, research, and development to jointly conduct basic theoretical innovation and forward-looking technological research; and overcome the constraints in the development of current laser information technology. Additionally, we will improve the level of key devices and the overall system, promote the standardization of laser information technology products and services, as well as the innovative development of ecological and service models of laser information technology.

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4.2 Building an industrial innovation platform to raise the level of technological innovation

By effective policy guidance and support, universities, scientific research institutes, and enterprises can become principal drivers of technological innovation. We will promote the integration of government, industry, research, research and application, and support relevant enterprises to jointly establish R&D institutions, industrial technology alliances, and other innovative organizations with scientific research institutes and institutions of higher learning. Considering constraints in technological development, we will fully consider the leading role of leading enterprises and the basic research capabilities of universities and research institutes; organize and perform coordinated innovations in production, teaching, research, and application across industries, fields, and regions; and advance the level of technological innovation.

4.3 Focusing on the protection of intellectual property rights and strengthening the training of high-end talents

It is proposed that the protection of intellectual property rights of emerging technologies should be strengthened, patent pools established, and technology transfer institutions supported to perform special tasks, especially those involved in space laser communication and laser display. The demand for high-level professionals who master key technologies and possess in-depth development capabilities should be investigated and predicted, an information base of high-level professionals in the laser information field should be established and improved, and industries and professionals should be gathered by promoting and strengthening the cooperation of the government, industry, universities, and research institutes. Furthermore, we will encourage colleges and universities to strengthen and enrich the formation of disciplines and specialties in the field of laser information technology, and to train scientific research and technical personnel.

4.4 Guiding the coordination of government, industry, university, and research institutions, and promoting cooperation in the transformation of achievements

It is proposed that the integration of government, industry, education, research, and application should be extensively promoted. Moreover, relevant enterprises should be supported to jointly establish R&D institutions, industrial technology alliances, and other innovative organizations with scientific research institutes and institutions of higher learning. This will enable them to establish and optimize coordination mechanisms and organizations at different levels, and to set up a cross-border exchange and cooperation platforms for laser information technology. Furthermore, key enterprises, institutions of higher learning, research institutes, and supporting suppliers in and out of the industry should be rallied to perform technology demand docking. The interdisciplinary dialogue and cooperation among laser information technology research teams in various universities and the rational sharing of data should be promoted. Further, pragmatic cooperation and collaborative innovations should be encouraged. Additionally, collaboration and cooperation among industry associations and academic organizations in relevant fields should be encouraged and supported to promote extensive exchanges, information sharing, and results sharing among research institutions and industry sectors. This will also enhance the level of relevant technological innovations and industrialization capacity.

4.5 Increasing policy support to guide the healthy development of the industry

It is suggested that based on the existing technology reserve base in China, the government should organize universities, scientific research institutes, and key enterprises to jointly establish state laboratories, engineering research centers, and other joint laser information technology research platforms or laboratories. The government should coordinate multiple forces to address important technical and fundamental application problems. The government should also increase R&D investment, track the development process of technology industrialization, adhere to the R&D thinking of scale-oriented application and bridge technology breakpoints, and improve the utilization efficiency and output level of innovative resources. To promote the formulation and implementation of key technical standards in the field of laser information under the unified coordination and management of the state, laser information technology-related industries need to be widely involved in basic hardware production, software development, core component manufacturing, physical machine network distribution platform, marketing, service, and several military and civil applications. The establishment of a technical standard system and key standards, as well as the support of standard compound testing and quality verification system, are required to ensure the development and sustainability of the industry.

4.6 Exploiting the advantages of industrial agglomeration to enhance the competitiveness of enterprises

It is proposed that industrial clusters in the field of laser information technology should be fully optimized and the procurement and supply costs of enterprises in the cluster area should be reduced. Furthermore, the communication and interaction between enterprises in various links should be facilitated and cooperation between enterprises should be promoted. Moreover, technology exchange should be promoted among enterprises in the cluster area to facilitate technological innovation, specialization of labor organizations should be promoted, and the networking of industry-related technical talents should be enhanced to achieve intensive benefits. The traditional industrial development framework which is closed should be prevented, and a laser information technology industry chain that is networked should be established. Additionally, innovative changes in business models, network structures, and content applications in various industrial clusters should be encouraged; exchanges and cooperation among the upper, middle, and lower reaches of relevant industrial chains in each industrial cluster should be strengthened; and transformation from single-point advancements to industrial agglomeration should be realized to promote the optimal division of labor among industrial clusters. We will adopt forward-looking policies on technology distribution in advance, support policy-oriented guidance, appropriate the stimulation of market environment and demand, and appropriate the expansion of industrial scale to substantially improve the competitiveness of enterprises.

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