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Progress and Prospect of Space Laser Communication Technology

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Abstract: Space laser communication technology is a major communication technology for space broadband information transmission and offers the advantages of high bandwidth, fast and convenient transmission, and low cost. It is the most efficient means to accomplish the "last kilometer" of information transmission. The aim of this study is to enable a systematic understanding of the development process of the space laser communication technology. The development of research and experimental verification of the technology in China and abroad in terms of satellite–ground, inter-satellite, space–ground, and inter-space links is summarized. The key technologies of laser communication are investigated in detail, namely acquisition tracking, communication transceiving, atmospheric compensation, and optomechanical design. Subsequently, five future development trends in space laser communication are summarized, i.e., high speed, networking, multipurpose, integration, and multiband. To further promote the research and industrialization of space laser communication technology, basic research plans are proposed, focusing on the research and development of core components, active participation in the formulation of international technical standards, and development of related industries.
Keywords: space laser communication; space–Earth integration network; high speed rate; laser networking; one-to-multiple laser communication

1 Introduction

Space laser communication technology, combining the advantages of ratio communication and optical fiber communication, is a type of communication mode with laser as a carrier. Space laser communication technology offers strong anti-jamming capability, high security, high information transmission speed, convenient band selection, and large capacity; furthermore, it is a light weight system with low power consumption and simple and flexible construction. Owing to these features, its strategic demand and application value in military and civil fields are significant [1, 2].

As an emergency communication scheme, space laser communication technology can be applied to earthquake relief, emergency, counter-terrorism, public security investigation, and other fields. Specifically, space laser communication technology can provide confidential military information for joint offense and defense involving multiple arms, and it offers outstanding advantages in local war, field networking, and information confrontation. In addition, benefiting from the advantages of high bandwidth, fast and convenient transmission, and low cost, space laser communication technology is considered as the best choice to accomplish the "last mile" of information

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transmission and the transmission of small and micro base stations of the fifth generation mobile communication technology (5G) [3]. China's space–Earth integration network project is a major construction project for implementing "no network security, no national security," including broadband backbone network of space network, access network, and other broadband spatial information transmission [4]. However, as it is difficult for the traditional microwave satellite communication method to satisfy the requirements of the space network transmission bandwidth of 40–100 Gb/s, a space laser network is urgently required to support this major project.

The importance and urgency of developing space laser communication technology has necessitated its comprehensive investigation. This paper summarizes the progress of space laser communication technology, analyzes its key technologies and future development trend, and proposes countermeasures and suggestions to promote the rapid development of laser communication technology in China.

2 Progress of space laser communication

Space laser communication has been successfully tested on various links, such as satellite–ground, satellite–satellite, satellite–aircraft, aircraft–aircraft, aircraft–ground, and inter-ground stations. [5]. The United States, Europe, Japan, China, Russia and other countries and regions have made breakthroughs in the key technologies of space laser communication, and have carried out a number of tests and verification (Fig. 1), actively promoting the application of space laser communication technology.

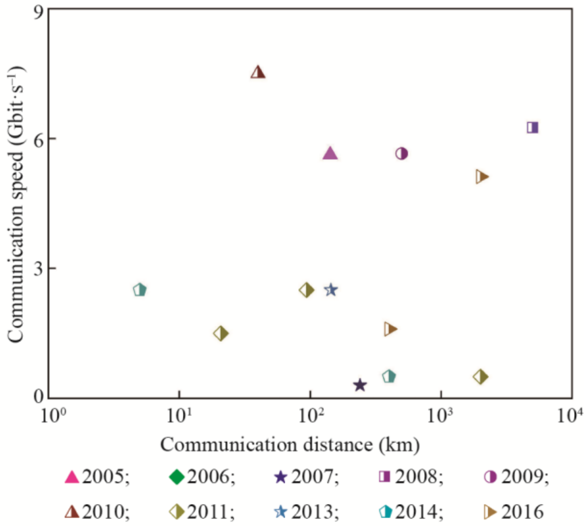

Fig. 1. Space laser communication test results.

2.1 Abroad main progress

(1) The United States, with support from the US National Aeronautics and Space Administration (NASA) and Air Force, was the first country to conduct research regarding space laser communications technology. Specifically, in 2000, in collaboration with the Jet Propulsion Laboratory, the NASA completed a laser communication demonstration system test. In October 2013, the lunar laser communication demonstration (LLCD) achieved two-way laser communications between a lunar orbit and multiple ground base stations of 4×10^5 km [6,7]. In November 2017, the NASA's innovative 1.5U CubeSat "Laser Communication and Sensor Demonstration" project verified the high-rate laser data transmission technology of future small satellites [8], and the maximum downlink rate of satellite–ground link was 2.5 Gb/s.

(2) Major countries in Europe have performed research regarding space laser communication technology. The European Space Agency performed the Semiconductor Laser Intersatellite Link test project in 2001, which verified the communication between low Earth orbit (LEO) and geosynchronous (GEO) satellites for the first time. In 2008, The German Space Center performed an in-orbit principle test of GEO–LEO long-distance space laser communication with Tesat, in which the transmission distance was 45 000 km, the antenna diameter was 135 mm, and binary phase shift keying coherence technology with a 1.06 μm carrier wave was adopted [9]. The maximum speed was 5.625 Gb/s, and the bit error rate was less than 10^{-8}. In 2015, Germany established an on-board adaptive optical communication ground station, which realized the high-rate transmission between on-board adaptive laser communication terminal and LEO with a transmission rate of 5.625 Gb/s. Furthermore, it realized two-way laser

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communications with the geostationary satellite Alphasat laser communication terminal with a bandwidth of 2.8125 Gb/s and an effective rate of 1.8 Gb/s [10,11].

(3) Japan has performed a series of demonstrations and verifications of satellite–ground laser communication. Both the Engineering Test Satellite (ETS-VI, 1995–1996) and Optical In-orbit Test Communication Satellite (OICETS, 2003/2006) programs have completed laser communication tests, realizing the world's first laser transmission between a low-orbit satellite and a mobile optical ground station [12,13]. In addition, Japan has begun developing miniature, lightweight, and low power consuming laser communication terminals, such as the advanced technology satellite program SOCRATES, through space optical communications. In 2014, a small optical communication terminal (SOTA) was completed for a laser communication on-orbit test [14]; the weight of the SOTA was 5.8 kg, the communication distance was 1000 km, and the downward communication rate was 10 Mb/s.

2.2 Domestic progress

In China, research pertaining to space laser communication technology began late; however, in recent years, remarkable progress has been made. Significant breakthroughs have been achieved in communication system technology, end-machine development, and laser communication technology.

In 2007, China completed the first dynamic in-flight space laser communication test, surpassing the dual-dynamic beam targeting and tracking technology, with the transmission rate reaching 300 Mb/s and the rate gradually increasing to 1.5, 2.5, and 10 Gb/s. Furthermore, the demonstration and verification of space–ground and space–space links were performed successively [15]. In 2013, a long-distance laser communication test between two fixed-wing aircraft was completed with a transmission rate of 2.5 Gb/s and a distance exceeding 144 km, exceeding the longest distance for similar demonstrations in Europe and the United States [16]. In 2011, China's first in-orbit test for the data transmission of a satellite–ground laser communication link was performed through the "Haiyang II" satellite [17], with the highest downward rate of 504 Mb/s. In 2017, the quantum science experiment satellite "Mozi" was used to conduct China's first in-orbit experiment of satellite–ground high-speed coherent laser communication technology [18], with the maximum downward speed of 5.12 Gb/s. In 2017, China's first high-orbit satellite–ground high-speed bidirectional laser communication test was performed successfully on the satellite–ground laser communication terminal carrying the "Shijian-XIII" high-throughput satellite [19], with the maximum rate being 5 Gb/s at a distance between the satellite and Earth of 40 000 km. These space communication experiments provide valuable information regarding the system design, capture and tracking technology, and atmospheric transmission characteristics of light waves.

3 Key technology analysis

With the development and progress of laser, optical, and optoelectronic technology, space laser communication technology continues to achieve breakthroughs. Based on the system function, space laser communication technology can be categorized into four types: capture and tracking, communication transceiver, atmospheric compensation, and opto–electromechanical design, which are described in the following section.

3.1 Capture and tracking technology

Space laser communication technology provides high power gain owing to the small divergence angle beam of the light source; hence, its requirements for beam capture and tracking are higher than those of microwave communication. The core targets of spatial laser communication technology are to realize fast, high-probability, and large-range beam acquisition; stable high-bandwidth; and high-precision beam tracking. Among these, beam capture adopts laser aiming technology and a system independent of coarse/fine tracking, i.e., the coarse tracking is composed of a closed loop by a large field camera and a servo turntable, which provides a large range of low-frequency band servo control. Precision tracking involves a closed loop of a high frame frequency camera and a fast vibrator, which provides a small range of high-frequency band servo control, thereby effectively suppressing the beam disturbance caused by the beam movement over a wide range and high-frequency jitter.

With the progress of laser technology, new technologies such as the intelligent transformation of laser beam and laser phased array have developed gradually and matured; they are applicable to the capture, alignment, and tracking system of space laser communication technology to change the traditional tracking mode and improve the tracking accuracy, speed, and reliability of space optical communication systems. Furthermore, the availability of small high-efficiency laser has enabled the tracking and pointing system to develop toward miniaturization, lightness, and integration. In addition, the laser communication tracking system can be simplified using the combination of coarse and fine tracking with the high precision and intelligent transformation of laser beams to ensure good tracking performances.

3.2 Communication transceiver technology

Space laser communication technology requires laser to exhibit large modulation bandwidth, high transmitting power, and narrow line width. The modulation methods of laser modulation technology can be categorized into direct and indirect modulation. Owing to the limitation of bandwidth and transmitting power caused by direct modulation, the modulation method for obtaining high transmitting power through a high-power fiber amplifier after an indirect modulation of a low-power seed laser source is mainly adopted currently. Based on the different parameters of the beam (such as intensity, frequency, and phase), modulation can be categorized into amplitude modulation, frequency modulation, phase modulation, and other different modulation modes that differ owing to differences in the corresponding devices of different wavelength systems. The main laser wavelengths of current space laser communication technology are 800, 1000, and 1550 nm. The 800 nm band of semiconductor lasers typically employ intensity modulation/direct detection; the 1000 nm band of Nd: YAG solid laser can be used in various modulation modes. The 1550-nm-band semiconductor laser is compatible with optical fiber communication systems; therefore, various high-speed modulation modes and erbium-doped fiber amplifiers can be used to realize high-speed high power emissions.

The high-speed detectors of laser communication receivers are coupled by optical fibers to adapt to the small detection cross-section of high-speed detectors and to facilitate system integration. Therefore, the coupling of space laser to optical fiber is one of the key technologies in the receiving part of laser communication, and the high efficiency coupling of optical fibers is mainly affected by pattern matching, alignment deviation, Fresnel reflection, absorption loss, and platform vibration. The existing fiber coupling methods mainly adopt optical adaptive, tapered fiber, and fiber nutation; however, no substantial breakthrough has been achieved. Hence, efficient fiber coupling has yet to be achieved in space laser communication systems.

3.3 Atmospheric compensation technology

When space laser communication technology is applied to satellite–ground, space–space, and space–ground links, the laser is affected by atmospheric turbulence when it passes through the atmosphere and receives power jitter occurs in the transmission, resulting in an error code in the system; this is more frequent in high-speed laser communications [20]. High-precision real-time wavefront distortion correction technology is an effective method for suppressing the effect of atmospheric turbulence on the wavefront of transmitted beams, i.e., multi-aperture wavefront detection using the Hartman sensor can correct wavefront distortions to a certain extent. However, challenges are encountered when using this technique, i.e., compensation of arrival angle fluctuation, wave surface deformation, and effect of boundary layer during air flight. As a solution, wavefront distortion compensation mirror technology can be introduced into the detection system for joint correction.

In recent years, significant progress has been made in atmospheric channels, from channel models to incoherent optical atmosphere transmissions. For example, based on the high-speed atmospheric transmission of partially coherent carriers by an active mode-locked fiber laser pumped dispersion-shifted fiber and a super high-speed continuous spectrum light source as a partially coherent carrier [21], compared with the coherent light source, the partially coherent light source carrier can effectively inhibit flicker caused by atmospheric turbulence intensity in 1 km of the atmospheric turbulence channel. Subsequently, it was proven that all-optical time division multiplexing technology can be applied in partially coherent optical communication systems to improve the transmission rate [22] up to 16 Gb/s.

3.4 Opto–electromechanical design technology

To reduce power loss in free space and improve the gain of the transmitting optical system, the communication beam must be transmitted near the diffraction limit angle. To guarantee the emission optical aperture, the beam emission gain must be increased for optical fiber coupling technology, beam shaping technology, and telescope surface design. To achieve breakthroughs in the key technology of near-diffraction-limit angle emission, shaping collimator technology of emitting laser source, and high-efficiency fiber coupling technology, the optimization selection method of matching different core diameter, beam scatter angles, and optical systems must be investigated through the development of laser technology.

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For optical base technology, a modularized and lightweight optical system must be achieved to satisfy the requirements of point-to-multi-point in-motion transmissions in future space laser communication networks [23]. Furthermore, the extensive application of laser technology has contributed to the standardization of many industries. For example, laser shaping transmission based on laser technology has contributed to the modularization and standardization of components and reduced the volume and cost of the entire machine.

4 Development trend

4.1 High speed

With the rapid development of space laser communication high-speed modulation and demodulation as well as transmission technology, the link rate of space–ground laser communication is expected to reach 100 Gb/s in the future. The major developments in high-speed wireless optical communication technologies in China and abroad are shown in Fig. 2. The technologies investigated were high-speed laser communication using higher-order modulation modes, such as quadrature phase shift keying (QPSK), quadrature amplitude modulation (QAM), and reuse methods such as wavelength division multiplexing (WDM), time division multiplexing (TDM), and reusability of the orbital angular momentum (OAM) for short distances (< 1 km) at the Tb/s level.

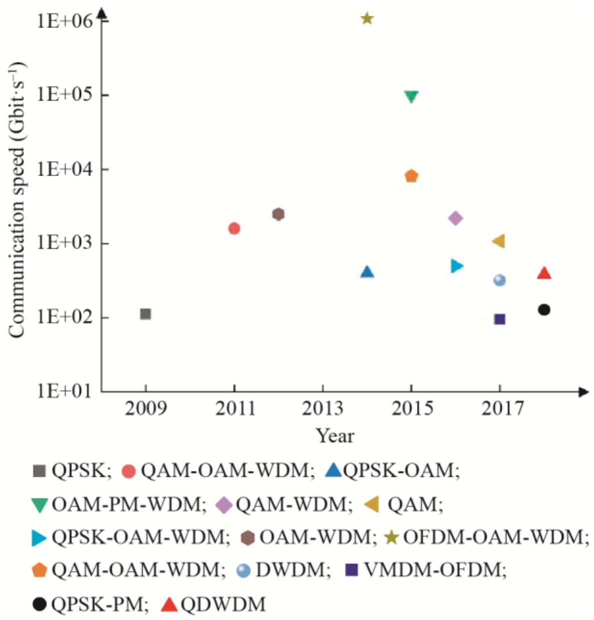

Fig. 2. Research on high-speed FSO in China and abroad.

Note: 1E+0n is 1 × 10^n. QPSK: quadrature phase shift keying; QAM-OAM-WDM: quadrature amplitude modulation (am)-orbital angular momentum multiplexing-wavelength-division multiplexing; QPSK-OAM: quadrature phase shift keying–orbital angular momentum multiplexing; OAM-PM-WDM: orbital angular momentum multiplexing-polarization multiplexing-wavelength-division multiplexing; QAM-WDM: quadrature amplitude modulation (am)-wavelength-division reuse; QAM: quadrature amplitude modulation; QPSK-OAM-WDM: quadrature phase shift keying-orbital angular momentum multiplexing-wavelength-division multiplexing; OAM-WDM: orbital angular momentum multiplexing-wavelength-division multiplexing; OFDM-OAM-WDM: orthogonal frequency division multiplexing-orbital angular momentum multiplexing-wavelength-division multiplexing; QAM-OAM-WDM: quadrature amplitude modulation (am)-orbital angular momentum multiplexing-wavelength-division multiplexing; VMDM-OFDM: vector module division multiplexing-orthogonal frequency division multiplexing; QPSK-WDM: quadrature phase shift keying -wavelength-division multiplexing; QPSK–PM: quadrature phase shift keying; DWDM: dense wavelength division multiplexing.

In 2009, the NEC Laboratory realized a 112 Gb/s test using QPSK and the MI/MO coherent detection method [24]; the University of Southern California realized a 100 Tb/s free space optical communication at a distance of 1 m indoors using 12 QAM-2 polarization 42 channel wave division technology [25]. In 2016, a 2.2Tb/s free-space optical high-speed communication experiment was conducted at King Saudi University with 12-channel WDM and 16-QAM modulation technology at an outdoor distance of 11.5 m [26]; subsequently, in 2017, spectral efficiency 32-QAM modulation was performed to surpass the 1.08 Tb/s free-space optical communication at a distance of 100 m in an outdoor dry desert region [27].

Through international cooperation and exchange, China has achieved significant progress in the research on high-speed space laser communication technology (Fig. 2). The Huazhong University of Science and Technology has performed a series of OAM ultra-high-speed wireless optical transmission experiments, achieving the maximum transmission rate of 1.086 Pb/s [28–30]. Although this study pertained to ultra-high-speed wireless optical transmissions over a short distance, the transmission rate achieved was comparable to the highest transmission rates achieved globally. In addition, research regarding laser transmission in long-distance high-speed spaces has progressed. For example, in 2018, the Changchun University of Science and Technology in collaboration with Zhejiang University used three channels of dense wavelength division multiplexing (DWDM) in a single carrier QPSK debugging at 40 Gb/s and performed a free-space optical communication experiment in a 1 km distance rate of 120 Gb/s [31]; consequently, a single carrier of 128 Gb/s and a three-channel DWDM total rate of 384 Gb/s were achieved in atmospheric transmissions [32, 33].

4.2 Networking

With increasing globalization and advancing information technology, a space network with seamless global coverage, high bandwidth, and destruction resistance without relying on the ground network is required urgently. Therefore, space-based broadband transmission networks based on space laser communication technology will be an important trend in the future.

The space laser communication technology has gradually developed from the point-to-point mode to relay forwarding and laser network construction. Because the main difficulties in the construction of laser networks are the small laser divergence angle, dynamic access of optical signals, and significant effects from the space environment, it is necessary to solve the “one-to-many” laser communication technology problem, obtain a dynamic routing solution, and aim for a joint laser and microwave communication system in the construction of laser communication networks. The design of point-to-multipoint optical transceiver antennas with a rotating paraboloid structure proposed by the Changchun University of Science and Technology can enable the networking of laser communication between multiple satellites. The optical principle is simple and is a major breakthrough in view of this difficulty [34].

4.3 Multipurpose

With the development of space laser communication technology, the advantages of high modulation rate, long transmission distance, and low energy consumption of space optical communications have become increasingly prominent. Currently, space laser communication technology is widely used in the broadband data transmission of interplanetary, starry, space–space, space–ground, and other links; furthermore, it has gradually expanded to deep space detection as well as underwater and ground access communications.

Deep space exploration refers to exploration activities pertaining to the Moon, distant celestial bodies, or space. It is an obvious method to understand the solar system and the universe, reveal the origin and evolution of the universe, and expand the living space of human beings. The implementation of lunar exploration projects is a prelude to China’s deep space exploration, followed by the implementation of the Mars exploration project [35,36]. As a new communication technology, underwater wireless optical communication offers large capacity, high bandwidth, high security, and strong anti-interference ability. It has become an important communication technology that the world powers are competing to develop [37]. Wireless optical transmission technology that uses visible light for data communication offers functions of lighting, communication, control positioning, etc. It can be easily integrated with existing basic lighting facilities and conforms to the national strategic idea of energy conservation and emission reduction. It will gradually become the main broadband transmission method for ultra-high-speed ubiquitous optical networking in the future intelligent era. In addition, in some special applications where optical cables cannot be laid, such as between islands, between urban buildings, and complex environments in the wild, space laser communication enables functionalities not afforded by optical fiber communication.

4.4 Integration

Owing to the advantages of laser in high-speed communication and precision ranging, the integrated technology of laser ranging and communication has received increased attention in recent years. The integrated design of laser ranging and communication is based on high-speed communication and considers precision ranging. The same laser beam and hardware platforms are used to realize ranging and information transmission; subsequently, the dual

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functions of ranging and communication are realized by the same set of equipment. In 2013, the NASA's LLCD system successfully performed the on-orbit demonstration verification of lunar and Earth high-speed laser communication and high-precision ranging [38], with the ranging accuracy reaching 3 cm. In 2014, the Beijing Institute of Telemetry Technology completed the integrated design of distance measurement and high-speed communication based on coherent communication [39]. In 2015, the Changchun University of Science and Technology proposed an integrated scheme of space target ranging, imaging, and communication [40], in which laser communication beacon light emission/receiving and laser ranging light emission/receiving shared an optical antenna.

In addition, the fusion of laser and microwave communication technology is a popular topic in academia currently; the technology includes mainly laser and microwave transceiver fusion, data processing fusion, laser modulation, and microwave signal generation. Currently, the mature microwave photonics technology is being applied to the laser transmission and processing of radar signals, and will be used in the fusion communication system of laser and microwave in the future.

4.5 Multiband

With the development of laser technology of various spectral segments, from ultraviolet to infrared and even to the terahertz band, practical laser technology has emerged. Because each spectrum segment offers certain advantages in anti-electromagnetic interference, cloud penetration ability, ad hoc network, etc., utilizing the communication system of different spectrum segments in space laser communication will enable a communication mode combining ultraviolet, visible, medium infrared, terahertz, and other spectral segments to be developed considerably. Therefore, research on multispectral communication should be strengthened to realize continuous barrier-free communication under different environmental conditions by the application of multispectral communication.

Compared with space laser communication technology, ultraviolet wireless optical communication technology can realize nondirect vision communication without strict capture, alignment, and tracking; this is highly advantageous in ad hoc networks, complex electromagnetic environments, and special terrain applications. In 2009, The California Institute of Technology theoretically studied the effects of a UV light scattering model, a detector, and the modulation mode and performed an experimental verification [41]. In recent years, terahertz wireless optical communication has achieved significant breakthroughs. In 2017, the terahertz research team of the Chinese Academy of Engineering Physics successfully performed a 21-km long-distance high-speed wireless transmission test with a single-channel real-time rate of 5 Gb/s [42], using a carrier of frequency 0.14 THz.

5 Policy suggestions

Currently, the development of space laser communication technology has not scaled at home and abroad. Owing to the significant development potential of this technology, countries worldwide have actively invested human and material resources to perform relevant research and steer the development of the industry. Commercial tests have been performed on satellite–ground, inter-satellite, space–space, and other links in the space laser communication technology in Europe and the United States, and relevant demonstrations and verifications have been completed in China. Therefore, a slight gap exists between China and developed countries and regions such as Europe and The United States in this field, and China, being a late starter, still has some advantages in some aspects. However, the problem of relying on the import of core components has not been solved. Therefore, through the national policy support, the top-level design as well as research and development must be strengthened to solve the most challenging technology problems and accelerate the promotion of space laser communication technology industrialization such that China can be on par with or even become a leading player in this field. To promote the development of space laser communication technology, the following policy recommendations are proposed.

5.1 Implementation of basic research plans

The development of space laser communication technology requires various optical fiber communication and optical design technologies. According to the new application characteristics, the formation of subversive technical concepts is inevitable, and basic research must be strengthened to achieve breakthroughs. Therefore, plans for scientific research on wireless laser broadband transmission and networking should be implemented in colleges and universities as soon as possible, such that breakthroughs in key core technologies can be achieved and China can lead the world in terms of basic research and key technology.

5.2 Attaching importance to research on core components

The technological level of optoelectronics and optical core components restricts the development of space laser communication technology in China, and the import dependence is high. Therefore, research units of components, universities, and enterprises should be organized to manage relevant key technologies, and the transformation of technological achievements must be supported comprehensively. By exploiting China's world-leading technological and product innovation in optical fiber communication technology and the industry as well as for the future application of space information network, China strives to realize independent intellectual property rights of core components.

5.3 Participating actively in formulation of space laser communication technology standards

With the maturity and commercialization of space laser communication technology, the formulation of its technical standards is particularly important. Therefore, a space laser communication technology standard plan should be implemented at the national level. By organizing universities, scientific research institutions, and relevant enterprises to perform research on technical standards and actively participate in the formulation of international standards, the development of space laser communication technology and industrialization in China should be promoted.

5.4 Guiding formation and development of related industries

With the continuous progress of space laser communication technology and the continuous expansion of its application fields, relevant industries have formed gradually; consequently, the correct guidance is required, and the healthy development of the industry should be promoted. Therefore, the following are suggested: (i) establish a reasonable plan for the industrial development of China's space laser communication technology field, (ii) guide universities, scientific research institutions, and enterprises to establish industrial cooperation plans, (iii) exploit basic research and key technologies to form effective achievements transformation, and (iv) promote rapid growth and development of the industry.

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