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Development of High-Brightness Solid-State Laser Technology

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Abstract: Laser propulsion, laser energy transfer, and other major research directions have a major demand for high-brightness solid-state laser technology; thus, relevant research remains the focus of international attention. This paper presents the macro demand for high-brightness solid-state laser technology and summarizes the current status of the technology research in China and abroad, its development trend, and the problems with further development. The key technologies of high-brightness solid-state lasers are analyzed, and some suggestions are proposed for future development. The slab laser and fiber laser have become the focus of research owing to their outstanding advantages. With the output power of a single laser constantly improving, a laser with high brightness output can be realized using the beam combination method. Key technologies should be promoted to form a key technology system as soon as possible, such as new laser materials, a high-ranking semiconductor laser pump source, high-precision packaging process, adaptive beam control, and key components for beam combination. The establishment of research projects for a solid-state laser represented by the surface gain slab laser technology is proposed, which has good potential for development. The research and development efforts of common basic technologies should be strengthened to create a solid foundation for the continuous improvement of the output brightness, conversion efficiency, and power-mass ratio of solid-state lasers in the future.
Keywords: solid-state laser; high brightness; technical route; key technology

1 Introduction

High-brightness laser technology refers to high-power, high-beam-quality laser generation, transmission, and control technology, and high-brightness solid-state laser technology specifically refers to laser generation technology that uses solid materials as the gain media. As the demand for high-power, high-beam-quality lasers in industrial processing, defense equipment, and other fields continues to increase, high-brightness solid-state lasers have generated much research interest and enthusiasm in academia and engineering because of their potential economic and military value.

Considering the gain medium configuration, high-brightness solid-state lasers are mainly divided into slab, sheets, and optical fibers. Slab lasers and fiber lasers have become popular research directions in the field of high-brightness solid-state lasers because of their outstanding advantages. The slab laser technology first realized the output of a high-brightness laser with a level of 100 kW. After a period of technological precipitation, new technological breakthroughs have been realized. The single fiber of the fiber laser has physical limitations and the output power is limited to the order of tens of kilowatts (the highest single fiber output of 20 kW was achieved in 2013). However, synthesis technology has further increased the output power.

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Starting with the macro demands of high-brightness solid-state lasers, this paper summarizes the representative high-brightness solid-state laser technologies in China and abroad and their development trends, and proposes a preferred technical path to achieve megawatt-level or higher-power laser output. Aiming at the key technologies and key problems in the field development bottleneck demonstration, we also put forward countermeasures and suggestions on the future development of China's high-brightness solid-state laser field.

2 Macro demand for high-brightness solid-state laser technology

2.1 Laser propulsion

Traditional space launches rely on large launch vehicles. Because the energy density of the chemical propellant is not high, propellant is considered as the main aspect of the mass composition of the launch vehicle, whereas the corresponding orbiting payload accounts for approximately 1.5%, and the launch cost is as high as $10 000/kg. As a new space launch method in the future, laser propulsion uses the plasma explosion gas mass generated by the interaction between the laser and the working medium to drive, and the effective load ratio can reach 15% [1]. It is estimated that the launch cost can be reduced by two orders of magnitude compared with the conventional method. Meanwhile, the safety of aerospace launches has been significantly improved with the use of nonenergetic working fluids. According to the engineering application assumption of laser propulsion [2], a pulse laser with an average power of 350 MW can be used to launch a 1000-kg payload into near-Earth orbit.

2.2 Laser wireless energy transmission

Lasers have outstanding characteristics including good monochromaticity, strong directivity, and energy concentration. They can transmit light energy to electrical equipment comprising photoelectric conversion devices at great distances, thereby achieving wireless energy transmission. Thus, lasers are used as a carrier for energy transmission. The volume and quality of the required equipment is only 1/10 of those of the microwave equipment, and it does not interfere with the microwave communication signal. Unmanned aerial vehicles, micro aircrafts, micro satellites, space detectors, wireless sensor networks, and other mobile loads urgently require new energy supply methods, so the application potential of laser energy transmission is vast.

2.3 Laser military applications

The use of directionally emitted high-energy laser beams to continuously focus on a target surface to destroy or invalidate the target is an important aspect of laser military applications. This type of application mode has the unique advantages of no delay, low combat cost, fast response speed, small incidental damage, strong anti-electromagnetic interference ability, and soft- and hard-killing. However, the problems of conventional battlefield combat firepower density and insufficiency are more prominent, and the military application of lasers is expected to change the traditional firepower engagement mode; hence, it is regarded as a subversive technology that can change the future war form and combat concept.

3 High-brightness solid-state laser technology development status

3.1 Development status abroad

3.1.1 Slab laser

The slab laser adopts a thin-plate-shaped gain medium. The laser is lased in the length direction of the gain medium, whereas the heat dissipation is in the thickness direction of the gain medium, thereby achieving a high-power, high-energy, continuous or pulsed laser output, and excellent beam quality. In 2009, the Northrop Grumman Company of the United States released the experimental results of a 7-channel conduction-cooled end-face pumped slab coherent composite laser output: the output power was 105.5 kW, the beam quality factor was less than 3, the electro-optic conversion efficiency reached 19.3%, the time from zero to full load output was only 0.6 s, and the cumulative running time exceeded 85 min [3,4]. This experiment became a milestone in the development of high-brightness solid-state lasers. In 2010, Marsh Corporation of the United States released the phased research progress on directed energy weapons (J-HPSSL), and obtained an output with an average power of more than 100 kW in the single-aperture laboratory of the immersed slab (ThinZag) laser [5].

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3.1.2 Thin disk laser

The gain medium of the thin disk laser has a sheet-like structure, and the heat dissipation and laser transmission are in the thickness direction of the gain medium, so the heat dissipation path is short and the clear aperture is large; thus, a high-power, high-energy, continuous or pulsed laser output can be realized. In 2012, Boeing of the United States integrated the German Yb:YAG thin-film technology, obtaining a laser output of 30 kW through a combination of multiple discs, and the electro-optical efficiency was greater than 30%; the main technical indicators reached the first of the Robust Electric Laser Initiative (RELI) Stage requirements, a follow-up development of the 50–100-kW laser system [6]. Moreover, American General Atomic-Aerospace Systems proposed a technical solution: immersing dozens to hundreds of thin-film laser media directly into a cooling fluid, and using submicron-scale fluid channels for efficient cooling of the laser media; in 2010, a single module of 60-kW power output was achieved. In 2015, two modules of 150-kW power output were achieved, and an 800-kW power output concept design based on related technical approaches was completed [7].

3.1.3 Fiber lasers

Fiber lasers use doped fibers that can be operated flexibly as gain media, and have excellent beam quality, high electro-optical efficiency (approximately 40%), easy heat dissipation, good reliability, and strong adaptability. However, there is an upper limit for the power output of a single-fiber laser (theoretical value is tens of thousands of watts); hence, it is necessary to achieve a higher power output through various synthesis methods, such as coherence/polarization/spectrum/chromatography/space. The US IPG company obtained a 10-kW power fiber laser output in 2009; in 2012, 1018-nm pumping was used to achieve a 17-kW power output of a 1075-nm laser based on the main oscillation power amplifier (MOPA) structure. The optical-optical conversion efficiency reached 94%, the output fiber core diameter was 50 μm, and the output beam quality M^2 factor was 2; in 2013, a single-fiber 20-kW power laser output was achieved [8]. Lockheed Martin of the United States used a high-density arrangement to achieve high-beam quality synthesis in 2015, with a combined power of 30 kW; in 2017, a 60-kW-level fiber spectrum synthesis light source prototype was achieved; in 2019, a 150-kW-level fiber spectrum synthesis was achieved with laser output [9].

3.2 Domestic development status

Presently, the research regarding high-brightness solid-state laser technology in China is focused on two aspects: slab and fiber.

3.2.1 Slab laser

In the 1990s, China began research into slab laser technology. In 2008, The Eleventh Research Institute of China Electronics Technology Group Corporation used the MOPA structure to achieve a slab laser output with a power of 11 kW [10], which was the first time a laser output of more than 10 000 W was achieved in China; in 2018, a single module of surface gain slab was used, where the two-pass amplification method achieved a laser output of 2.6 kW [11]. In 2018, the Institute of Applied Electronics of the Chinese Academy of Engineering Physics used a segmented doped slat to obtain a laser output of 20 kW [12]. In 2019, the Institute of Physical and Chemical Technology of the Chinese Academy of Sciences used conventional large-size slats to obtain a laser output of 60 kW under low temperature and cryogenic conditions [13].

3.2.2 Fiber lasers

Regarding high-power fiber lasers, many domestic institutions have conducted in-depth research and created a large repository of theories and experimental findings in engineering technology. In 2017, the Laser Fusion Research Center of the Chinese Academy of Engineering Physics designed a single-fiber laser system with 976-nm direct single-end pumping, and used a nationally produced fiber material and fiber device to achieve a 10.6-kW power output of the single-fiber laser system [14]. In 2018, using the long-distance distributed side pumping technology, a stable laser output with a maximum power of 11.23 kW was achieved based on the MOPA structure, with the slope efficiency of 82.5% [15]. In 2017, Tsinghua University adopted a single seed source, achieving a 3.9-kW power Raman laser output via a two-way pump structure and gain fiber length control, with the beam quality M^2 factor of 1.49 [16]. Furthermore, the National University of Defense Technology used the time-domain stable seed source and 1018-nm laser co-band pumping technology to achieve a single-fiber 10 000-W power output, and the beam quality M^2 factor was 1.86 [17]. In 2019, the Shanghai Institute of Optics and Precision Mechanics used the self-developed large-mode field double-clad gain fiber and passive devices with double-end pumping technology to achieve the final power amplifier output power of 10.14 kW; the central wavelength was 1070.36 nm. The spectral bandwidth of 3 dB was 5.32 nm, the maximum light-to-light conversion efficiency of the main amplification stage was 87.8%, and the slope efficiency was 89.2% [18].

4 High-brightness solid-state laser technology development trend

4.1 Technical routes

4.1.1 From the perspective of laser technology characteristics

Currently, the laser technologies that have achieved an output power of more than 100 kW are predominantly fiber lasers, slab lasers, and immersed liquid-cooled thin-film lasers, while gaps in practical applications remain for other technical routes.

An upper limit exists for the power output of single-fiber lasers; thus, a higher power output needs to be achieved through various synthesis methods, such as coherence/polarization/spectrum/chromatography/space. Presently, there are two main technical routes to achieve this: ordinary line width and narrow line width.

For slab lasers, the output power of a single link can be very high, and a higher power output can be achieved through coherent/polarization/spectral/timing synthesis methods. However, compared with fiber lasers, the reliability is slightly worse and the thermal management is more complicated.

Although the immersed liquid-cooled thin disk laser can solve the problem of excessive concentration of waste heat in the gain medium of the high-energy laser, the temperature of the liquid is not uniform because of the laser transmission through the cooling liquid, and the thermal and optical coefficient of the liquid is two orders of magnitude higher than the solid, which seriously affects the beam quality of the output laser. In addition, the electro-optical efficiency is relatively low.

Fiber lasers have the advantages of reliability, thermal management, and platform suitability. However, because of the limited output power of single fibers, it is very difficult to achieve megawatt laser output. A breakthrough has been made in the key technology of the megawatt power output of the slab laser. While ensuring the quality of the beam, a power output above the megawatt level is expected to be realized for slab lasers sooner and more easily than for fiber lasers.

4.1.2 From the perspective of laser R&D practice

After arranging the various technical routes investigated in China and abroad (Figs. 1 and 2), the following preliminary technical judgments can be obtained: (1) Within tens of kilowatts of output power, no special requirements exist for a high beam quality, continuous output, and laser spectral linewidth; because of its high efficiency, high reliability, and good adaptability, fiber laser technology has a comparative advantage, and it is expected to realize engineering applications earlier; within a 100–200-kW output power level, the advantages of the high beam quality and high reliability of fiber laser technology can only be barely maintained; whereas, in the output power level of 300 kW or more, the fiber laser technology has not met the basic requirements of high brightness, and the beam quality is difficult to guarantee. (2) Regarding the bulk solid laser technology represented by slab and thin disk, for power requirements in the range of tens of kilowatts to several megawatts, there are technical solutions for high-power and high-beam quality outputs in terms of continuous system, pulse system, laser line width narrowing requirements, etc. However, the optical path design is complicated; there are many discrete components, and the highly efficient and reliable laser product technology research cycle will get extended.

4.2 Development trend

(1) Fiber laser technology has difficulty meeting the application requirement of an output power of more than 300 kW, and the solid laser technology represented by slab and sheets is the preferred way to achieve a power output above the megawatt level (Fig. 3).

(2) The research progress of new large-size gain media, such as high-quality laser crystals/ceramics, can greatly increase the output power of a single gain module, which provides important support for the continuous improvement of single-channel laser power.

(3) To improve the performance of solid-state lasers, such as the brightness, conversion efficiency, power-to-mass ratio, and power-to-volume ratio, the fundamental measures include increasing the brightness through synthesis, improving the brightness and efficiency through the cryogenic gain medium, and designing innovative gain module structures.

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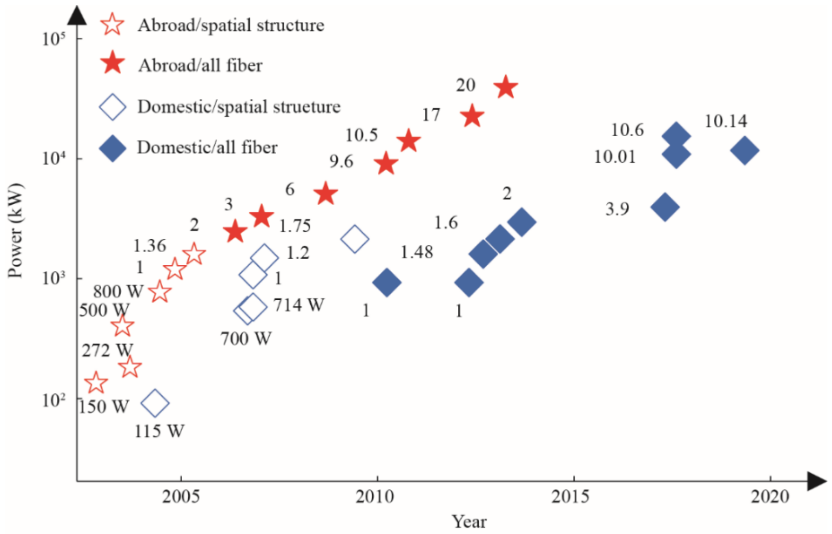

Fig. 1. Development of single-fiber optics.

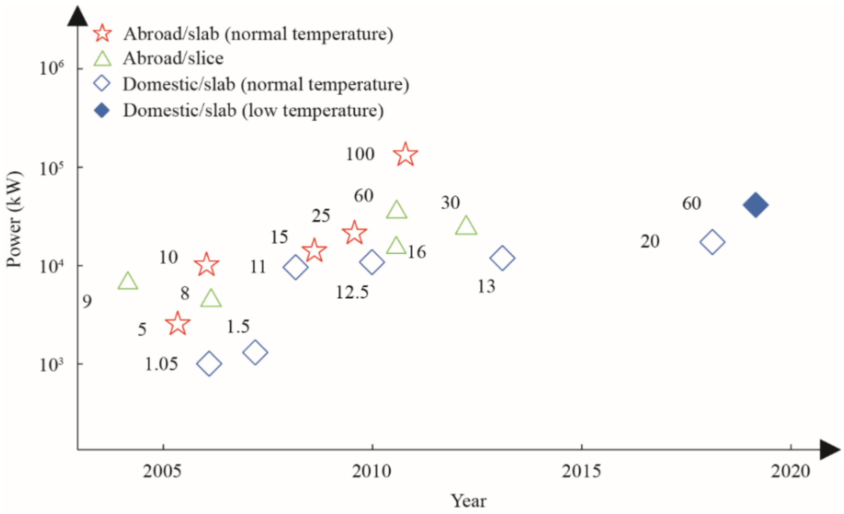

Fig. 2. Development of single-caliber solid-state lasers with block structure represented by slab and slice.

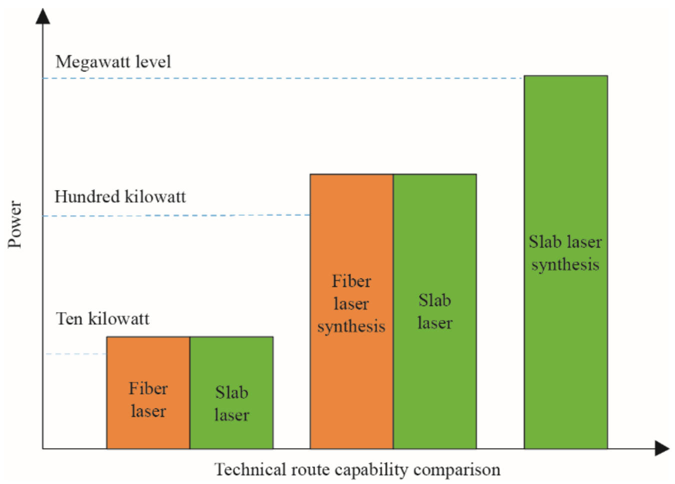

Fig. 3. Abilities of different technical routes.

5 Challenges for the development of high-brightness solid-state lasers

The brightness of the laser is directly proportional to the power and inversely proportional to the second power of the beam quality M^2 factor, and can be improved by increasing the power and improving the beam quality. Because of the “thermal effect,” the beam quality tends to decrease with the increase of power. Eventually, the laser brightness does not increase as expected with the increase in laser power, and can even decrease. To this end, the development of high-brightness solid-state lasers must focus on solving the following technical challenges.

(1) The gain medium is the key to realizing a high power of the gain module. The increase in the output power of single-aperture lasers is faced with the difficulty of high-power laser amplifier modules having high optical quality, high optical accuracy, and high heat flux density performance characteristics. If this problem cannot be overcome, the output capability of the solid-state laser will be severely restricted.

(2) The high-brightness solid-state laser has extremely high requirements for the uniformity of the pump light. Because of its inherent structural characteristics, the high-power laser diode pump source is faced with the problems of large beam divergence angle, inconsistent horizontal/vertical directions, and uneven beam intensity distribution. This constitutes a clear constraint on the output power and beam quality of solid-state lasers.

(3) The large amount of waste heat generated by the laser gain module during operation needs to be treated in time. If the waste heat cannot be cooled in time and uniformly accumulates in the gain medium, it will cause the thermal stress and thermal distortion of the gain medium, which will seriously affect the output power and beam quality of the laser.

(4) With the continuous increase in output power, the factors that thermally affect solid-state lasers tend to be prominent. The aberration contained in the output laser gradually increases with the increase in power, and even exceeds the limits of the spatial resolution and aberration correction capabilities of adaptive optical systems for laser beam purification, which in turn results in the inability to correct the aberration.

(5) Semiconductor laser pumping technology has contributed to the high efficiency and high brightness output of solid-state lasers, leading the technological revolution in the laser field. Because of insufficient research on the physical mechanisms such as nonlinear effects of the medium and thermal damage, the average brightness of a single laser remains limited.

6 Analysis of key technologies of high-brightness solid-state laser

Full-link technology and process research has been conducted on high-brightness solid-state lasers from 100 kW to megawatts, striving toward key breakthrough technologies, such as high-performance gain dielectric materials; high power density pump coupling; high heat flux density, heat dissipation, and temperature control; strong light transmission damage-resistance; wavefront control; and beam synthesis, to lay the technical foundation for future megawatt-level high-brightness laser output and engineering applications.

6.1 Structural design, preparation, and testing of high-performance gain medium

The gain medium structure determines the core performance of the solid-state laser and guides the basic design directions, such as pump coupling, heat dissipation, and temperature control. To achieve a high-brightness laser output, the gain medium structure should have high gain and low wavefront distortion, that is, to meet the performance requirements of high power, high efficiency, uniform pump coupling, high heat flux density, high power laser transmission, and high nonlinear threshold.

For the design of the surface gain slab, the research includes: mastering the absorption, gain, and heat dissipation characteristics of different configurations of gain media; selection of the design of pumping and cooling structures; analyzing the adjustable range of the structural design parameters; and proposing the structural design plan in combination with the process feasibility. For the current gain medium structural scheme, the factors should be comprehensively analyzed in accordance with the requirements of the processing technology, and the best results should be sought through modeling and optimization. Moreover, a mathematical model should be established of the relevant laser amplification operation through multiple iterations to form a power amplifier gain medium structural design-optimization scheme of different power levels.

6.2 Light field distribution design and control of high-power-density pump

Research on high-power laser diode pump sources and highly integrated pump-coupling optical components should be performed, striving toward a breakthrough in the high-efficiency, high-power coupling and

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homogenization technology of pump lights, including high-efficiency and high-power output of laser diodes; line width control of the array output laser; divergence angle control; high-density stacking; efficient conversion, integration, and waveguide design of pump-coupled optical components.

The laser diode pump source has a narrow application field and range because of its inherent structural characteristics. Different applications require the laser diode to have different output spots and light fields. Attention should be paid to the research on the collimation and shaping of the output beam, and various engineering analysis software should be used to carry out the modeling and simulation of various semiconductor lasers to form an advanced design scheme to improve the quality of the output beam.

6.3 High-heat-flux conduction-cooling technology

This technology includes heat sink design and processing, uniform thermal contact between the gain medium and the heat sink, and low-stress packaging. Furthermore, it involves technical analyses such as thermal field analysis, flow field simulation, heat sink structure stress field analysis, and verification of environmental construction. Phase transformation heat sinks, nanoscale thermal interface materials preparation, etc., are also valuable frontier directions. Vacuum welding packaging technology with low stress and a low thermal interface void rate is the core technology of slab gain dielectric lasers.

For the high heat flux conduction-cooling of the gain module, micro-channel heat exchange technology is mainly used. The key points of related research are: design optimization of microchannel structure, improvement of microchannel structure processing technology, optimization of coolant selection, and the influence of various parameters (channel cross-sectional shape and aspect ratio, friction coefficient in microchannels, different coolants, etc.) on the flow and heat dissipation performance in microchannels.

6.4 Wavefront control technology

The beam quality of the output laser is the core index of the high-brightness solid-state laser, and it places extremely high demands on the spatial resolution and aberration correction amount of the adaptive optical system used for laser beam purification. The construction of an adaptive optical system with multiple anamorphic mirrors has been explored, using multiple different types of wavefront correctors in the phase conjugate position to compensate for the components most suitable for correction in the aberration; therefore, the advantages of different types of wavefront correctors are organically integrated to optimize the time and space characteristics of the adaptive optical system. Moreover, research should be conducted on the architecture and performance of the real-time processing subsystem of the adaptive optical system, the adaptive boundary of the large-unit adaptive optical system should be determined, and the real-time processing delay should be effectively compressed to improve the closed-loop speed of the adaptive optical system.

6.5 Laser synthesis technology

Synthesizing technology is an effective way to achieve solid-state laser output power scaling and amplification. It is used to overcome the power limitation of solid-state laser single-aperture output because of the size of the gain medium, and to achieve solid-state laser output with a high average power and high beam quality. Related research focuses on spectral synthesis, coherent synthesis, and time-series synthesis, among others.

Spectral synthesis breaks through the technologies such as laser beamlets with narrow linewidth and specific frequency spectrum, dispersion elements with good performance and high damage threshold, and dense beamforming with high integration. In the field of coherent synthesis, the technology of laser beam single-frequency (better than megahertz linewidth) characteristic control, high-precision wavefront control, multi-channel initial phase synchronization control, and highly integrated dense beamforming have been studied. In the field of timing synthesis, research is focused on pulsed laser beamlets, high resistance to light damage, and highly stable beam-combining devices.

7 Suggestions

7.1 Strengthen exploratory research and focus on technological innovation

A high-brightness laser technology evaluation system should be studied and established, and technical foresight, research judgment, and tracking research in the field should be strengthened. Investigations should be problem oriented, and should grasp the development trend of technology, lay out in advance the disruptive technology that may lead to the change in high-brightness solid-state laser technology, conduct forward-looking basic research, and should pay particular attention to new system lasers such as special waveguides and surface gains that are innovative in dielectric-structured gain technology. Necessary support should be provided for original exploratory research on which consensus has not been formed, as well as to encourage scientists to explore freely and overcome cutting-edge scientific problems, strive to make breakthroughs in original theory and original discovery, and lead the major field of high-brightness solid-state lasers with technological innovation progress.

7.2 Implement major project deployment and breakthrough key technologies

Taking the major future needs of China as the starting point, based on the field-development strategic planning and the solid foundation already obtained in the field of solid-state laser materials and device technology, major scientific and technological projects of next-generation high-brightness solid-state laser technology should be established, implemented, and actively deployed in laser technology with high average power, high peak power output, and high spectral power density output. Meanwhile, in response to the urgent needs and weak links in the development of China's high-brightness laser technology, technical breakthroughs need to be identified and a more focused approach should be taken to give full play to the advantages of the national pool of equipment and research. Further, development of a group of key common technologies and leading technologies should be strived toward to realize the engineering application demonstration of high-brightness solid-state lasers as soon as possible, and strong support should be provided for the construction of a strong technological country and the development of a smart society.

7.3 Strengthen international exchanges and build a high-level talent team

Multichannel layout encourages the establishment of regular academic exchange mechanisms and scientific research cooperation with internationally renowned laser technology research institutions. The cultivation of laser technology talents and echelon construction should be strengthened. This would create objective conditions conducive to the growth of outstanding young talents, and cultivate a group of strategic scientific and technological talents, leading science and technology talents, young scientific and technological talents, and technological innovation teams with an international vision and a high level.

References

[1] Zhang L. Mechanism Investigation of laser propulsion with solid propellant [D]. Hefei: University of Science and Technology of China (Doctoral dissertation), 2008. Chinese.

[2] Kantrowitz A. Propulsion to orbit by ground-based lasers [J]. Astroautics and Aaeroautics, 1972, 10(5): 74–76.

[3] Marmo J, Injeyan H, Komine H, et al. Joint high power solid state laser program advancements at Northrop Grumman [C]. San Jose: Society of Photo-Optical Instrumentation Engineers, 2009.

[4] McNaught S J, Asman C P, Injeyan A, et al. 100-kW coherently combined Nd:YAG MOPA laser array [C]. San Jose: Frontiers in Optics 2009/Laser Science XXV/Fall 2009 OSA Optics & Photonics Technical Digest, 2009.

[5] Goodno G D, Komine H, McNaught S J, et al. Coherent combination of high-power, zigzag slab lasers [J]. Optics Letters, 2006, 31(9): 1247–1249.

[6] Selinger M. Boeing fires new thin-disk laser, achieving solid-state laser milestone [EB/OL]. (2008-06-03) [2019-10-01]. http://www. boeing.com/news/releases/2008/q2/080603a_nr.html.

[7] Wilmington M A. Textron defense systems awarded funding for the DARPA HELLADS Program [EB/OL]. (2008-10-03) [2019- 10-01]. http://www.globalsecurity.org/military/systems/aircraft/ systems/hellads.html.

[8] Jeong Y C, Boyland A J, Sahu J K, et al. Multi-kilowatt singlemode ytterbium doped large-core fiber laser [J]. Journal of the Optical Society of Korea, 2009, 13(4): 416–422.

[9] Sabourdy D, Kermene V, Desfarges-berthelemot A, et al. Power scaling of fiber lasers with all-fibre interferometric cavity [J]. Electronics Letters, 2002, 38(14): 692–693.

[10] Wang C, Tang X J, Xu L J, et al. Investigation on thermal effect of high power slab laser with 11 kW [J]. Chinese Journal of Lasers, 2010, 37(11): 2807–2809. Chinese.

[11] Li N, Zhang W Q, Liu Y, et al. Yb:YAG surface gain slab laser amplifier [J]. Chinese Journal of Lasers, 2018, 45(11): 1–5. Chinese.

[12] Tang C. Active beam quality control technology for high energy solid laser system [C]. Chengdu: The Fourth Symposium on the Development of Atmospheric Optics and Adaptive Optics, 2019. Chinese.

[13] Guo Y D. Beam quality control technology for high energy solid laser system [C]. Chengdu: The Fourth Symposium on the Development of Atmospheric Optics and Adaptive Optics, 2019. Chinese.

DOI 10.15302/J-SSCAE-2020.03.008

[14] Lin H H, Tang X, Li C Y, et al. Home-made single-fiber laser system achieved 10.6 kW laser output [J]. Chinese Journal of Lasers, 2018, 45(3): 329. Chinese.

[15] Lin A X, Zhan H, Peng K, et al. 10 kW-level pump-gain intergrated functional laser fiber [C]. Hangzhou: 2018 Asia Communications and Photonics Conference (ACP), 2018.

[16] Gong M L, Yan P, Xiao Q R. High power fiber laser technology and future development [C]. Weihai: Seminar on Advanced High Power High Energy Laser Technology and Application, 2017. Chinese.

[17] Liu Z J, Zhou P, Ma P F. Research progress and analysis of high power optical fiber laser [C]. Weihai: Seminar on Advanced High Power High Energy Laser Technology and Application, 2017. Chinese.

[18] Chen X L, Lou F G, He Y, et al. Home-made 10 kW fiber laser with high efficiency [J]. Acta Optical Sinica, 2019, 39(3): 415– 417. Chinese.