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Development Trend of Ultrafast and Ultra-intense Lasers and Their Scientific Application

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Abstract: Ultrafast and ultra-intense lasers have ultrafast temporal and ultra-intense focal intensity properties. They can create unprecedentedly extreme experimental conditions with ultrahigh time resolution, ultrahigh temperature, ultrahigh pressure, as well as ultrahigh strength field. An ultrafast and ultra-intense laser is an important tool for fundamental frontier research intended to extend the knowledge of mankind. This study starts with an analysis of the application and development demands of ultrafast and ultra-intense lasers, and then systematically investigates the research status of such lasers in China and abroad. Based on this study, the developing routes and targets of ultrafast and ultra-intense lasers, as well as related technologies needed for achieving these targets, are proposed. In particular, we propose key steps for developing ultra-intense lasers with an ultrahigh peak power and high repetition rates, and emphasize the studies on related technologies and ancillary components. Furthermore, several suggestions are proposed for the development of ultrafast and ultra-intense lasers in China, including a strengthening of fundamental research, improvement in personnel training, enhanced international cooperation, and the promotion of market applications, with an aim to provide references for the steady development of laser technologies in China.
Keywords: ultra-intense and ultrashort laser; femtosecond laser; attosecond laser; petawatt laser; development trend

1 Introduction

After the invention of the laser, ultrafast lasers with femtosecond pulse duration were quickly developed based on the mode-locking technique. This type of ultrafast laser pulse was widely and quickly applied to physics, biology, chemistry, and material research fields, leading to laser spectroscopy research into ultrafast fields. In 1999, Prof. A. Zewail obtained the Nobel Prize in chemistry owing to his original and innovative research on femtosecond chemistry. In 2018, the Nobel Prize in Physics was given to the designer of the famous chirp pulse amplification (CPA) technique [1], which promoted research into ultra-intense laser intensity.

Ultrafast and ultra-intense lasers (UULs) are special light fields with an ultrafast temporal property and ultrahigh peak power simultaneously. This special laser can create an ultrafast pulse duration, ultrahigh electrical field, ultrahigh pressure, and ultrahigh temperature in the lab, which will promote the development of frontier research in physics, chemistry, biology, material, medical, and interdisciplinary sciences. UULs can be considered the most important tool, and even a unique and irreplaceable method, for extending human knowledge at the frontier of basic sciences.

Ultrafast and ultra-intense techniques are pushing forward the progress of basic frontier sciences, while some

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novel applications or researches require UULs with higher properties at the same time, which motivating the need for the development of UULs. In this article, the current research status and scientific requirements of UUL technologies are investigated, the development routes and targets of UULs are discussed, with the aim of providing some references for the steady development and progress of national laser technologies.

2 Analysis of UUL requirements

Scientific applications in basic frontier research using UULs require improved laser properties and some new or unapplied parameters to further explore the basic principles of internal matter. Depending on the different research targets of the frontier sciences, the requirements of UULs can be divided into two parts.

2.1 Ultrafast lasers and their scientific applications

The future development in this area can be sub-divided into attosecond, even zeptosecond sources, and femtosecond lasers of which the multi-dimensional parameters are precisely controllable within a wavelength extended from the extreme ultraviolet (EUV) to terahertz (THz) band.

Attosecond, even zeptosecond, lasers are being used to study faster ultrafast processes inside matter by applying sources with a shorter pulse duration. It is necessary to develop a high-performance attosecond pulse with a higher pulse energy, shorter pulse duration, and higher photon energy. Pushing the photon energy to the hard X-ray band and the gamma-ray band, and pushing forward the pulse duration to the timescale of tens of zeptoseconds (10^{-21} s) will help explore the dynamics from the atomic/molecular level to the nuclear scale [2].

However, many important ultrafast processes in atoms/molecules, materials, biological proteins, and chemical reactions occur within the femtosecond time scale, which require laser pulses with a femtosecond pulse duration. For the development of this area, ultrafast processes of complex systems or complicated processes, and the precise control of these complex ultrafast processes, urgently need to be explored. These requirements require femtosecond pulses with spectra extended into the infrared-THz and deep UV-EUV ranges. Furthermore, precise controllable multi-dimensional parameters in terms of time, amplitude, phase, spectrum, polarization, and spatial mode, among other factors, should be helpful for this ultrafast spectroscopy. In all, multi-dimensional parameters of precisely controllable femtosecond lasers with a wavelength of the EUV to THz band are needed in this area.

2.2 Ultra-intense lasers and their scientific applications

Ultra-intense lasers can be sub-divided into two directions according to their differences in application: low-repetition-rate ultrahigh-peak-power lasers (LRR-UPPL) and high-repetition-rate high-average-power lasers (HRR-HAPL), where low repetition rates indicate no more than 10 Hz and high repetition rates indicate no less than 1 kHz.

Only using ultra-intense lasers can people obtain the same extremely physical conditions as found in stars and inside a nucleus in the laboratory. With LRR-UPPL, it is possible to study not only frontier physics problems of extremely tiny systems, such as laser electron acceleration, light-nuclear physics, and gamma rays, extremely huge systems in astrophysics, such as supernova outbursts, solar flares, and black hole accretion disk jets, but also frontier basic studies that can extend human knowledge, such as gravitational waves, dark matter, and vacuum physics. Furthermore, LRR-UPPL can provide powerful scientific tools for vital national studies such as on laser particle accelerators, nuclear transmutation, high-energy physics, laser fusion, and laser medicine.

HRR-HAPL with a high average power is an extremely important tool for safety and environmental physics in space, particularly for ultra-intense lasers with high repetition rates that can adapt to special space environments. HRR-HAPL can generate intense second-stage beams such as proton beams, electron beams, neutron beams, x-rays, γ-rays, and THz waves, which can be used as novel driving tools for important basic research and applications such as light-nuclear reactions, laser propellers, laser fusion, nuclear waste disposal, and diseases therapy.

3 Current research status of UUL

3.1 Ultrafast lasers and their scientific applications

3.1.1. Attosecond laser

A fundamental limitation in the development of attosecond pulse lasers during the past 20 years has been the low single pulse energy. The international mainstream solution to this problem is to establish a high-power and long-wavelength femtosecond ultrafast laser system as the driving laser. ELI-ALPS, which is being constructed at a cost of hundreds of millions of Euros in Hungary, can produce attosecond pulses with a high peak power and high average

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power using two petawatt (PW) laser systems [3]. The long-wavelength mid-infrared femtosecond laser system can generate attosecond pulses with a higher photon energy and shorter pulse width [4]. Research into an attosecond laser with a high repetition rate has also made important progress [5]. In addition, the generation of attosecond pulses using an X-ray free electron laser (XFEL) has also been originally verified. XFEL has obvious advantages in generating high-power attosecond pulses with a high photon energy (hard X-ray and gamma-ray bands).

Domestic studies on attosecond lasers have been concentrated in several institutions such as the Shanghai Institute of Optics and Fine Mechanics (SIOM), the Institute of Physics (IOP), and the Xi'an Institute of Optics and Precision Mechanics (XIOM). The current domestic studies have been left behind in comparison to those conducted in developed countries. In 2009, the SIOM measured the pulse duration of attosecond pulse train and obtained an attosecond laser pulse near the Fourier transform limit. In 2013, the IOP produced and measured a single attosecond pulse with a pulse duration of 160 attoseconds. XIOM has undertaken numerous tasks in attosecond pulse laser research. Domestic colleges and universities, such as Huazhong University of Science and Technology, East China Normal University, Peking University, and National University of Defense Technology, are also conducting attosecond laser related studies. In addition, some institutions have also carried out a series of studies on high-power lasers to produce high-energy electron and gamma rays.

3.1.2. Femtosecond laser

Based on nonlinear optical methods, the wavelength of a femtosecond laser was already extended from the visible-NIR range to the deep UV-EUV and infrared-THz ranges. Free electron lasers (FEL) can obtain wavelength tunable femtosecond pulses within the UV-EUV and THz ranges, achieving a high pulse energy; however, such a facility is expensive and complicated. To explore complicated ultrafast processes, precisely controllable multi-parameter and multi-wavelength femtosecond lasers have been under development.

Many domestic research groups have adopted imported commercial femtosecond lasers to extend the laser wavelength using nonlinear effects; here, SIOM, ShanghaiTech University, and Xi'an Jiaotong University had finished a series of studies in multi-wavelength femtosecond lasers and their precise control. In 2019, the Dalian Institute of Chemical Physics built an FEL that can output a continual wavelength tunable femtosecond pulse within the 50–200 nm spectral range [6]. The China Academy of Engineering Physics (CAEP) also obtained a high energy and wavelength tunable THz ultrafast laser using FEL. These lasers will greatly support basic frontier studies in ultrafast spectroscopy.

3.2 Ultra-intense lasers and their scientific applications

Ultra-intense lasers are rapidly being developed in the field with fierce competition, and there are more than 50 PW laser facilities around the world [7].

3.2.1. LRR-UPPL

Ten PW laser facilities have been built in the European Union, the United States, Japan, South Korea, and Russia. Recently, several countries have proposed large projects on the building of 100–200 PW lasers. Nearly 40 scientific research agencies from 10 European countries have proposed the Extreme Laser Infrastructure (ELI) project, aimed at a final 200 PW laser, which was approved as a part of the development route of scientific facilities, and achieved an output peak power of 10 PW in 2019 [8]. The Apollon laser facility [9] in France achieved a peak output power of 5 PW in 2018 and will achieve 10 PW in 2020 according to their new plan. The Vulcan laser facility [10] in the UK was arranged to upgrade the peak power from 1 to 10 PW using the technology of optical parametric chirped pulse amplification (OPCPA). In Russia, a 200 PW laser project was proposed by Exawatt Center for Extreme Light Studies (XCELS). It will contain 12 beams that will be coherently combined [11], where the peak power of each beam will be 15 PW with a pulse duration of 25 fs. The picosecond laser project of LFEX in Japan achieved a PW peak power with an output pulse energy of as high as 2 kJ, which will used mainly for research into inertial confinement fusion (ICF) and astrophysics. In South Korea, a laser facility [12] with a peak power of 4.2 PW at a repetition rate of 0.1 Hz was built at Gwangju Institute of Science and Technology (GIST). In the US, the output parameters of the laser facility of OMEGA EP at the University of Rochester are 1 kJ, 1 ps, and 1 PW, and a 100 PW laser project was proposed.

Domestic studies on LRR-UPPL started early and quickly, and a competitive research team with a strong capability and reasonable manpower structure was established. Since 1996, the "Workshop on Strong Field Laser Physics," which takes place every two years, has promoted communication and development in related research areas. In recent years, a series of achievements have been achieved, including first class results based on the global standard. In 2017, a laser system with a peak power of ~5 PW was built at the CAEP based on the technology of OPCPA and nonlinear crystals of LBO [13]. In SIOM, a series of achievements were made during the last few years. The SULF laser beam based on CPA technology was first amplified with a peak power of 5 PW in 2016 and was upgraded to 10 PW in 2017 [14]. Based on the route of OPCPA, a 1 PW amplifier was demonstrated in 2015 [15]. In 2018, a project called SEL for 100 PW peak power was started. Meanwhile, several labs in some universities have proposed programs for multi-PW laser facilities.

3.2.2 HRR-HAPL

HRR-HAPL mainly contains ultrafast disk lasers and ultrafast fiber lasers. By solving the problem of the thermal effect in the gain medium, a single disk laser can reach an average power of thousands of watts. With the advantages of compaction, good thermal conductivity, high conversion efficiency, and high repetition rates at over 1 MHz, a femtosecond fiber laser was developed extremely quickly. Limited by nonlinear effects in terms of the fiber, pulse energy and peak power of a single femtosecond fiber laser remain at a low level and often operates at the front end.

In 2012, Mourou organized a popular and large research plan called the “International Coherent Amplification Network (ICAN)” in the European Union [16], which is aimed at developing ultrafast fiber lasers and beam combination techniques to achieve HRR-HAPL with a high average power. These lasers can be used as the driving laser for the next-generation of high-energy laser accelerators. Under the ICAN plan (target of 10 J, 100 fs, and 10 kHz), a research group at the University of Jena, Germany has conducted many studies on the temporal and spatial combination of femtosecond fiber lasers. They obtained a kW level average power with high repetition rates by using a coherent beam combination (CBC) of 16 femtosecond fiber lasers. They also proposed a novel concept for multi-terawatt fiber lasers based on spatial CBC (16 × 32) along with a temporal combination or coherent pulse stacking in passive cavities, which is expected to obtain much more economical parameters of 300 fs and 100 TW HRR-HAPL [17].

There has been no overall arrangement regarding HRR-HAPL studies in China. Currently, only a few research groups at SIOM, Beijing University, National University of Defense Technology, and Tianjing University, among other institutes have worked on several key techniques such as the manufacturing of high performance gain fiber, disk laser amplification, femtosecond fiber oscillator, fiber CPA, spatial CBC, coherent pulse stacking, and high energy pulse compression, and some institutes and universities have made significant progress in gain fibers with a large mode area. Owing to the potential wide applications in micro-manufacture areas, many laser companies in China are developing femtosecond fiber lasers with an average power of tens of watts, and a few of them already have created femtosecond fiber laser products with an average power of higher than 50 watts. However, many key optical elements still require importing, and there are fewer key elements with independent intellectual property rights. Over all, studies in this area have been scattered throughout the country, requiring a systematic planning and design.

4 Development routes and targets of UUL

4.1 Ultrafast lasers and their scientific applications

4.1.1. Attosecond laser

To support research into basic physical processes such as ultrafast inner shell electron dynamics, electron spin-orbit dynamics, and complex structures such as macromolecules and even biological macromolecules, the photon energy of the attosecond pulse needs to break through to the level of 1 keV or even 10 keV. The key technologies involved include a mid-infrared laser system with high power, few cycles, and stable carrier-envelope phase; high-brightness keV attosecond laser pulse generation; high-resolution electron and multi-electron momentum characterization; and pushing the photon energy up to a hard X-ray and gamma-ray levels using Compton scattering.

To investigate the deep inner shell electronic dynamics and even the dynamics of atomic nuclei, the pulse duration needs to break through to the level of the zeptosecond. When the photon energy of an attosecond pulse reaches the level of 10 keV or even the gamma-ray level, the attosecond pulse duration has the possibility of entering the zeptosecond timescale. The key technologies involved include those related to improving the production efficiency, ultrafast measurement technologies for application, and pulse duration measurements within the zeptosecond range.

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4.1.2. Femtosecond laser

For the development of ultrafast spectroscopy, except for the temporal property of a femtosecond pulse, the spectrum and polarization are also important parameters that can be used in ultrafast spectroscopy. Some important aspects that should be developed in this area are as follows: the development of MHz broadband femtosecond pulse in EUV-THz band; development of high-performance multi-wavelength femtosecond pulses; a multi-wavelength frequency comb; special time-space controllable pulses in the temporal shape, spatial mode, and polarization; the development of a GHz ultrafast laser pulse; novel stable ultrafast spectroscopy for pure and simple micro or complex systems; and research on precise control of brain science, cancer, biological development, and regeneration using multi-parameter controllable ultrafast lasers.

4.2 Ultra-intense lasers and their scientific applications

4.2.1. LRR-UPPL

LRR-UPPL must address many important frontier physical questions that can extend human knowledge using LRR-UPPL as a research tool. The most important research in this area is the improvement of the peak power from 100 PW to 1 exawatt (EW), and achieving a high focused intensity of 10^{25}W/cm^2, which can provide extremely advanced physical conditions. To improve the experimental efficiency and stability of these types of studies, the repetition rate of a laser pulse should be improved considerably. Meanwhile, a special optical field distribution such as a vortex light field should be developed for many different applications. Wavelength-tunable and space-time accurate controlling laser pulses will extend such applications further. With an increase in focused intensity, the requirement for a temporal contrast continues to increase. Therefore, innovative studies on related improvements and measurements of the temporal contrast should be developed. In addition, new technologies on the focus of LRR-UPPL with a large beam size are essential, and can solve the cost problem of a laser system while improving its focal intensity.

The peak power and repetition rate are two of the most important parameters for the future development of LRR-UPPL. Peak powers of 100, 500, and 1000 PW (1 EW) are expected to be achieved in 2025, 2030, and 2035, respectively, and the repetition rate will be improved accordingly. First, for the first 5 years, the target is to build laser facilities with a peak power of 100 PW running on a single shot and 10 PW running with repeated rates. Some new discoveries are expected to be obtained in the fields of vacuum physics, lab astronomy, and anti-matter physics, among others using advanced laser facilities. Second, for the next 10 years, the technology of large-scale gratings and other important optical components will be broken through. Combined with CBC technology and a higher pump energy, a 500 PW LRR-UPPL can be achieved, which can be used for research into gravitational waves and dark matter. Finally, for the next 15 years, both the pump laser pulse energy and the size and damage threshold of the compression grating will be continually improved. An EW laser can then be achieved using CBC technology. Through the development of an innovative optical focus system, a focal intensity of 10^{25}W/cm^2 can be achieved, which can be used to explore some new basic frontier studies, such as QEDs. Furthermore some new methods and theories based on laser–matter interactions as an innovative route to generate a higher peak power should be explored.

4.2.2. HRR-HAPL

According to the current technique level domestically, technical prospects, and national requirements, the developing trends of HRR-HAPL are summarized as follows. In the first 5 years, focus should mainly be on the key techniques such as femtosecond fiber CPA, spatial CBC, coherent pulse stacking, and pulse compression of high pulse energy. The difficulties, complications, and costs of a HRR-HAPL facility should be reduced using innovations in the route and design. During the next 10 years, TW ultra-intense pulses with kHz repetition rates are expected to be obtained in the lab, which will be used in laser electron acceleration, and high-flux attosecond pulses based on HHG. The novel high-flux second stage sources will be used in ultrafast dynamic processes of atom/molecule and important materials. During the next 15 years, 10 TW ultra-intense pulses with kHz repetition rates are expected to be achieved using a spatial CBC. We hope that the cost per watt of a femtosecond fiber laser can be largely reduced owing to the wide applications of femtosecond fiber lasers in various industries. A 10 TW laser will be used to drive a small size particle accelerator for medical application, and the generated high-flux neutron beam will be used to explore the laser fusion process and the disposal of nuclear waste.

5 Key related technologies

(1) Attosecond laser

The key techniques that should be followed in the future mainly include the following: a high energy single attosecond laser pulse, a high average power (high repetition rate) attosecond laser, a high photon energy attosecond pulse, and a miniaturized high repetition rate attosecond pulse to expand the application of an attosecond pulse. The relevant technologies include high-quality few cycle (including mid-infrared) laser pulse technology, simple and convenient attosecond laser pulse measurement technology, new attosecond laser application technology, high-quality high-brightness hard X-ray and gamma-ray generation technology, and zeptosecond laser technology.

(2) Femtosecond laser

For the femtosecond laser area, we should pay attention to a multi-wavelength high-performance femtosecond laser technique, bi-/multi-comb femtosecond technique, MHz high-performance ultrafast laser within the VUV-EUV and infrared-THz spectral range, a radial polarized/vortex femtosecond laser, a GHz ultrafast laser based on quantum dots, a VCSEL ultrafast laser, multi-parameter precisely controllable femtosecond laser in terms of time, spectrum, polarization, space, phase, and amplitude.

(3) LRR-UPPL

As the focal intensity and temporal contrast are the most important parameters for LRR-UPPL, newly related technologies, such as a pulse amplification and high energy pulse compression, spatial focusing, improvement and measurement of the temporal contrast, need to be developed. The key techniques will include a high flux pulse amplification by CPA or OPCPA defending the limitation of the gain medium scale, manufacture of laser crystals or nonlinear crystals with a large size, Raman amplification in plasma and quasi-OPCPA (QPCPA), design of a compressor with a new structure, development of large size gratings with a high damage threshold, CBC with a large size and high intensity multi-beam, improvement and single-shot measurement of the temporal contrast, the space-temporal monitoring for the large size beam, wavefront shaping of high-energy large size beam, the design of an innovative focusing system with high quality, accurate spatial-temporally modulation of ultra-intense light field, ultra-high intensity pulse compression, generation, and application of vortex or radial polarized ultra-intense light field.

(4) HRR-HAPL

The key techniques for HRR-HAPL in the future mainly include a novel femtosecond fiber amplification, novel disk amplification of a femtosecond laser, techniques on spatial CBC, coherent pulse stacking, and a related, special fiber design and manufacture for novel femtosecond laser amplification, high energy pulse compression, related pump lasers with high repetition rates, management of the thermal effect, a high performance gain fiber, a high performance fiber grating, and precise control of the light field.

6 Suggestions

(1) Considering significant national long-range requirements in the solar system and deep space, health, energy sources, and nuclear physics, as well as important basic international science requirements in vacuum physics, dark matter, and gravitational waves, long-term development strategic planning should be made as soon as possible. In addition, a center for basic science or a collaborative innovation center on UULs should be developed, which will provide steady support for important studies in the above areas. Basic research, especially more original studies should be emphasized. Related key and “bottleneck” techniques should be classified, arranged, and studied in advance.

(2) Studies with original and innovative approaches are the most important for achieving breakthroughs in basic science and technology. It is necessary to build up a better management system and scientific environment to inspire new ideas. The importing and development of more outstanding researchers, particularly first-class researchers with original minds and disciplinary science backgrounds, are needed. More outstanding researchers will bring about more original achievements, which will allow China to lead the world in related sciences and technologies in the field of UULs.

(3) Basic science research aims at increasing human knowledge and needs both domestic innovation and the intelligence and wisdom of overseas researchers. It is necessary to build up a stronger international collaboration to attract outstanding researchers from overseas to work together and speed up and promote some important areas of study. It will be possible to build up some strategic and significant scientific facilities and conduct collaborative researches along with other countries such as Russia and Asian countries under the Belt and Road framework,

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particularly in certain extremely important prospective areas and research fields in which China has already reached a first-class level, such as LRR-UPPL. Similar to the ELI project and international Event Horizon Telescope project, this type of international sharing of basic scientific results will help promote the international influence of national science and technology.

(4) To allow basic scientific achievements to better serve the national economic and social development more quickly, institutes and universities should build up a tighter collaboration with companies to speed up the transformation of scientific and practical technical results on UULs. At the same time, intellectual property protection and management, as well as technical risk prevention, should be emphasized.

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