Chirped-Pulse Amplification

Ultrahigh peak power production from compact short-pulse laser systems

Introduction of chirped-pulse amplification (CPA) enabled the latest revolution in production of high peak powers from lasers through amplification of very short (femtosecond) laser pulses to pulse energies previously available only from long-pulse lasers. CPA has rapidly bridged the gap from its initial modest demonstrations to multi-terawatt and petawatt-scale systems in research facilities and universities, as well as numerous lower-power scientific and industrial applications.

With the advent of a mode-locked laser, it was quickly realized that the future of scaling lasers to even higher peak powers will require solutions beyond the most obvious direct amplification of an ultrashort laser pulse in a laser amplifier. Femtosecond laser pulses pack very high peak powers and associated electric fields even in modest-energy pulses, resulting in their proneness to inducing beam distortions and optical damage in the optical components through which they propagate, such as self-focusing and its temporal counterpart, self-phase modulation. An important condition for efficient extraction of stored energy from the laser amplifier is the operation at fluences (pulse energies per unit area) close to the characteristic saturation fluence for the given laser amplifier material, a demand easily met in nanosecond amplifiers without the risk of inducing optical damage. Operation at those same fluences with pulse durations up to a million times shorter is not possible without inducing significant self-focusing and self-phase modulation, resulting in catastrophic optical damage. One method for overcoming such energy density (beam intensity) limitations would be the increase of the laser amplifier aperture commensurate with the increase of peak power, but the required apertures would be impractically large, laser systems would be highly inefficient as they would not operate near saturation fluence, and would suffer from problems such as transverse parasitic lasing.

It turns out that the hint to a solution of this problem can be found as early as the time of the demonstration of the first laser, but the idea has been initially proposed to overcome a different issue – the power limitations of radars [1]. In 1985 it was realized by the group at the University of Rochester led by Gérard Mourou that this technique, termed chirped-pulse amplification (CPA) [2], can also be applied in the optical domain, with revolutionary consequences for laser science and technology and its applications. The idea of CPA is indeed simple and beautiful: given the limitations encountered by ultrashort laser pulses while propagating through the laser amplifier, let us manipulate the ultrashort pulse in a controllable and reversible fashion such that the laser amplifier never encounters a short, high power pulse, and only the laser system components compatible with such high peak powers can be exposed to it. It is well known that the intensity limits associated with optical damage for standard reflective and diffractive optical components are orders of magnitude greater than those associated with nonlinear effects and damage in transmission through the laser amplifier. If a convenient way exists to controllably stretch, amplify, and subsequently recompress the ultrashort laser pulse close to its original pulse duration, it is possible to circumvent the damage limitations of laser amplifiers and scale the short-pulse lasers to extreme peak powers.

THE AUTHOR

IGOR JOVANOVIC

Igor Jovanovic is an Associate Professor of Nuclear Engineering at Penn State University. He received his undergraduate degree from the University of Zagreb in 1997 and his Ph.D. from the University of California, Berkeley in 2001. He is one of the pioneers of the technique of optical parametric chirped-pulse amplification. After receiving his Ph.D. he joined the Lawrence Livermore National Laboratory as a staff physicist, and in 2007 he became an Assistant Professor of Nuclear Engineering at Purdue University. Since 2010 he directs the Intense Laser Laboratory at Penn State University and leads a research group studying high-power laser technology, laser-matter interactions, and advanced radiation detection science and technology.

Igor Jovanovic
Department of Mechanical and
Nuclear Engineering
The Pennsylvania State University
233 Reber Building
University Park, PA 16802, USA
Phone: +1 814 867 4329
Fax: +1 814 863 6382
E-mail: ijovanovic@psu.edu
Website: www.mne.psu.edu/IJ

Components of a laser CPA system

Reversible manipulation of the temporal characteristics of ultrashort laser pulses is possible if a conjugate set of optical devices termed stretcher (or expander) and compressor is used (see Figure 1). An inherent property of ultrashort pulses that can be used for their controlled stretching and recompression is their broad spectral bandwidth. Short pulse duration can be achieved only if coherent light consists of a range of wavelengths which are carefully and orderly synthesized – such as the pulses produced by mode-locked lasers. The stretcher operates by introducing large, well-characterized dispersion, i.e. time delay of different spectral components of the ultrashort pulse to produce a long, chirped optical pulse. The compressor operates on the same principle, with dispersion that closely matches that produced by the stretcher, but opposite in sign. Thus the ultrashort pulse initially generated in a mode-locked laser first undergoes stretching in the pulse stretcher (to ps-ns durations), amplification to high energies in the laser amplifier, followed by compression close to its original pulse duration in the pulse compressor.

Several important stretcher and compressor implementations have emerged in the optics community, and they all have in common the utilization of dispersive properties of materials or specially constructed devices. Relatively large (~10^4), high-fidelity stretching ratios can be achieved in optical arrangements based on diffraction gratings, which dominate the world of ultrahigh peak power CPA systems. Diffraction gratings are presently available in apertures on the order of 1 m^2, allowing direct recompression of pulses to powers exceeding 1 PW [3]. Moderate stretching and compression ratios can be achieved with prism-based devices, optical fibers and Bragg gratings implemented either in bulk material or fibers. Finally, relatively small stretching and compression ratios can be achieved by using the natural dispersion of bulk material or specially designed reflective dielectric stacks (chirped mirrors). All of those methods are in use today, with the choice among them usually determined by the requirements for the final pulse energy and pulse duration at the CPA system output.

The CPA process can result in both amplitude and phase distortions, preventing the optimal recompression of the laser pulse and achieving a high peak power. Stretching and recompression over many orders of magnitude in pulse duration is a process that requires high accuracies in the design and manufacturing of optical components and in the construction of the stretcher and compressor. Additional spatiotemporal distortions are frequently introduced in stretchers and compressors. For this reason, and to minimize system size, stretchers and compressors are usually designed to provide a minimum stretching ratio compatible with achieving the required pulse energy at the onset of significant pulse distortions in the laser amplifier. Such distortions lead to phase and spectral modification of the ultrashort pulse and can cause difficulties with pulse recompression. Additional distortions can occur in the amplification process due to the amplifier material nonuniformities, nonlinearities, and thermal distortions. Significant effort has been expanded in the short-pulse laser community to achieve effective dispersion compensation, with much success. At the same time, the possibility of flexible dispersion control has emerged and has enabled numerous practical applications. Active dispersion control in CPA systems can be achieved effectively by using specialized pulse shaping devices that can selectively delay or attenuate individual spectral components of a laser pulse and utilize spatial light modulators or acousto-optic programmable dispersive filters.

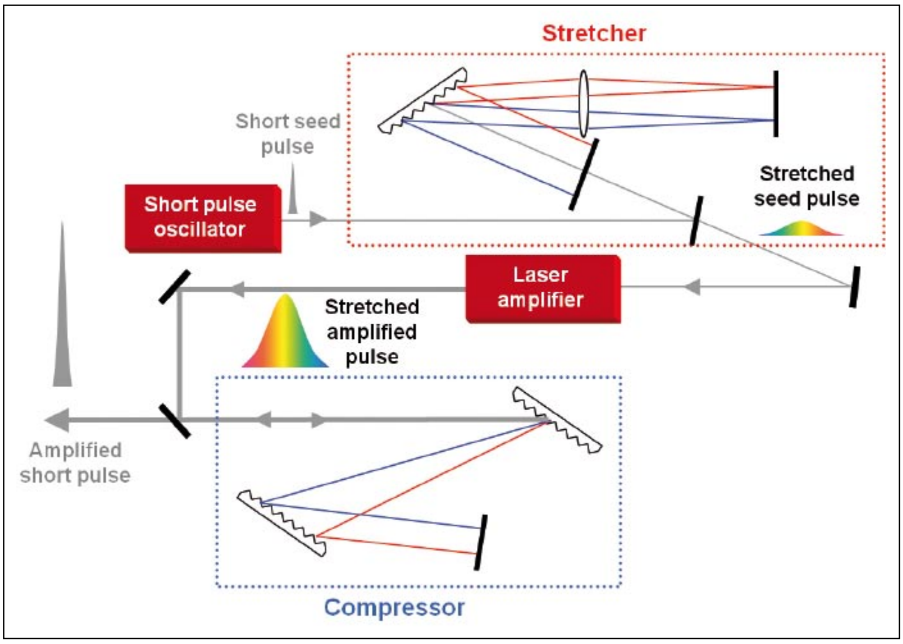

FIG. 1: **Conceptual schematic of a chirped-pulse amplification-based laser system.**

The pulse recompressed at the output of the CPA system exhibit peak powers that usually greatly exceed that producible in long-pulse lasers. For example, a standard modern tabletop CPA laser system, such as the one shown in Figure 2, found in university laboratories and small research institutes exceeds the 400 TW peak power available from the largest nanosecond laser system ever built – the recently completed National Ignition Facility at Lawrence Livermore National Laboratory in California. Of course, CPA pulses carry much less energy and thus their advantages will be prominent only in applications in which high peak powers and focal intensities are desired.

Applications of CPA

Numerous applications have emerged for CPA in the past two decades, and they could be broadly classified into scientific, industrial, medical, energy, and military/security. Scientific applications were iden-

FIG. 2: **High-energy multipass cryogenically cooled Ti:sapphire amplifier.** (Credit: Amplitude Technologies)

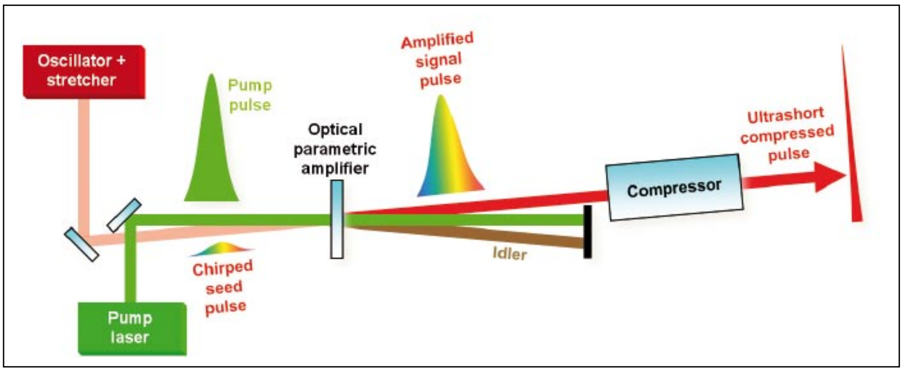

FIG. 3: **Conceptual schematic of an optical parametric chirped-pulse amplification system.**

tified first, and are to this day driving the advances in CPA technology. Some of the most striking examples include

- the ultrafast pump-probe experiments for chemistry, biology, and material science,
- studies of the dynamic properties of materials,
- production and studies of hot dense matter resembling extreme processes in astrophysics (high-energy density physics),
- generation of even shorter (attosecond) laser pulses for studying ultrafast processes, and
- pushing the "intensity frontier", where previously unexplored high-field physics is studied at focused intensities that today already exceed 10^{22} W/cm^2.

Industrial applications have been motivated primarily by the notion that ultrafast laser pulses can interact with materials very differently from long pulses, enabling high-precision removal of very small amounts of materials without melting, a property very useful in materials processing. Such high-precision material removal is also very interesting in medical applications, where minimal damage to surrounding tissue can result when ultrashort pulses are used in surgical procedures. A particularly interesting application of CPA is in the development of future energy sources based on inertial confinement fusion. Experimental evidence exists that ultrahigh intensity lasers based on CPA can significantly relax the requirements on the laser drivers and targets in fusion facilities. In the military arena the use of ultrashort pulses is being considered for efficient production of long, conductive plasma channels in the air (plasma filaments), and high-energy density physics is being used to validate the performance of nuclear weapons.

THE UNIVERSITY

Pennsylvania State University

University Park, PA, USA

The Pennsylvania State University (popularly known as Penn State) is one of largest public research universities in the United States, spanning 24 campuses and a virtual World Campus offering distance education. The student population of Penn State is close to 90,000, with half of the students located at the flagship campus at University Park. Penn State is ranked among the top 15 public universities in the United States and has one of the largest federal and industry-funded research programs, with a particular strength in science and engineering. Optics and laser research is conducted in the Colleges of Engineering and Science, but also in the university-affiliated Applied Physics Laboratory and the Electro-Optics Center.

www.psu.edu

One of the most exciting discoveries applicable to all of the areas discussed above is that CPA lasers can serve to produce ultrashort, ultrabright beams of ionizing radiation from relatively compact, inexpensive systems. Since its initial demonstration, CPA has been used to produce X-rays, gamma-rays, terahertz radiation, as well as energetic electron, proton, and heavier ion beams. The recent rapid advances in the technique of laser wakefield acceleration of electrons are very promising for replacing expensive and large accelerator facilities. This is especially useful in frontier scientific research, medical therapy and diagnostics, and security.

CPA limitations

Development of CPA has already encountered several important challenges and limitations, which are the subject of vigorous international research and development activities. For example, the unprecedented development of intense, ultrahigh power laser facilities in Europe through the Extreme Light Infrastructure (ELI) project will require continuous and rapid advances in CPA technology.

Important challenges and limitations for this technique include the compressible energy, pulse duration, prepulse contrast, and average power. For example, the ultimate limit in CPA pulse energy is presently determined by the size and damage threshold of the final compressor component (usually a diffraction grating), which is exposed to the high-energy recompressed pulse. Numerous advances have been made to increase the available grating sizes, optical damage thresholds, and to coherently tile gratings into larger apertures. The output pulse duration is limited by the bandwidth of the available laser gain media used, with Ti:sapphire, Yb:glass and Nd:glass being the most popular choices today. With the advent of ultrahigh peak powers and peak intensities it became apparent that the temporal fidelity of the pulse, i.e. the ratio of the power contained in the main pulse to the power contained in the light arriving at earlier times can be as critical as other parameters. Prepulse contrast ratios required in short pulse experiments today frequently exceed 10^{10}, the level attainable only recently in selected CPA systems. Finally, industrial applications and especially laser-driven particle accelerators will require higher repetition rates. This issue is presently being addressed by innovative laser designs such as fiber lasers, by development of new materials, and by advances in diode pumping technology.

Optical parametric chirped-pulse amplification (OPCPA)

In the last decade we witnessed a rapid development of a new implementation of CPA which does not utilize direct laser amplification – termed the optical parametric chirped-pulse amplification (OPCPA) [4]. Such systems are similar to CPA systems, but utilize a laser to pump a nonlinear medium (optical nonlinear crystal such as beta-barium borate, lithium triborate, and potassium dihydrogen phosphate). Through a nonlinear difference-frequency generation parametric process it is possible to efficiently transfer energy from an energetic nanosecond pump pulse to a stretched femtosecond pulse (see Figure 3). It is important to note the difference in the motivation for ultrashort pulse stretching here compared to conventional CPA: OPCPA is an instantaneous process in which comparable pulse durations are needed for the stretched signal and the pump – typically on the order of nanoseconds in high-energy applications. OPCPA systems exhibit many attractive characteristics, such as high gain, very broad spectral bandwidth that only weakly depends on gain, spectral tunability, and negligible thermal load. Those characteristics led to the widespread use in the preamplifier stage for high-energy short-pulse lasers [5], and in schemes that seek to produce higher peak powers through even shorter pulses than those available from CPA systems [6]. Another attractive application has been the prepulse contrast enhancement, where it has been demonstrated that the OPCPA performance greatly exceeds that of comparable CPA systems based on direct laser amplification.

Conclusion

The advent of CPA in the optical domain and its application to boost the peak power through reduced pulse durations has revolutionized the field of lasers. We are still witnessing the wave of innovations in many areas of science and technology that resulted from this important insight. CPA is presently an indispensible technique in scientific research, but also in industrial and medical applications. Furthermore, it is making inroads into even more areas traditionally dominated by a different technology, such as particle accelerators. There is no doubt that we will continue to experience an evolutionary development of CPA technology, with occasional breakthroughs such as OPCPA that have a high probability to support the de facto equivalent of the Moore's Law for laser power and the scope and importance of laser applications.

References

[1] G. E. Cook: "Pulse Compression-Key to More Efficient Radar Transmission", IEEE Proc. IRE 48, 310 (1960)

[2] D. Strickland, G. Mourou: "Compression of amplified chirped optical pulses", Opt. Commun. 56, 219 (1985)

[3] M. D. Perry et al: "Petawatt laser pulses", Opt. Lett. 24, 160-162 (1999)

[4] A. Dubietis, G. Jonusauskas, A. Piskarskas: "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal", Opt. Commun. 88, 437–440 (1992)

[5] I. Jovanovic et al.: "Optical parametric chirped pulse amplifier as an alternative to Ti:sapphire regenerative amplifiers", Appl. Opt. 41, 2923 (2002)

[6] C. Hernandez-Gomez et al.: "The Vulcan 10 PW Project", J. of Physics: Conf. Series 244, 032006 (2010)