Current Status of Chirped-Pulse–Amplification Technology and Its Applications

S.-W. Bahk

Laboratory for Laser Energetics, University of Rochester

Chirped-pulse amplification (CPA) is a technology that has become the basis of high-peak-power lasers.[1] The intensity of the electromagnetic field has been dramatically increased since its invention. CPA is an amplification scheme that allows safe amplification of a pulse to high energy. A short low-energy pulse is stretched in time and is injected into an amplifier. After amplification to high energy, the pulse is compressed back to the original short pulse. We discuss key components of CPA in this summary.

We will first discuss the optical pulse compressor and stretcher. The compressor is made up of two parallel gratings in double pass or four gratings in single pass.[2] The accumulated holographic phase through the grating pair is a quadratic function of the frequency, which introduces chirp in time. Large-scale tiled compressors for petawatt facilities have been demonstrated at OMEGA EP[3] and PETAL.[4] A stretcher is a compressor with an imaging system.[5] The imaging system renders the effective optical distance between the two gratings negative as the image of the first grating is formed behind the second grating. The original lens-based imaging system in the stretcher has been replaced with a reflective Offner imaging system.[6]

Amplifiers are based on either optical pumping and stimulated emission or parametric amplification. Laser-diode pumping is most efficient but flash lamps or secondary pump lasers are commonly used for optical pumping. The most widely used femtosecond amplification medium is titanium sapphire, which can amplify a wide range of frequencies, is not easily saturated even at high-energy pulses, and has high amplification efficiency. It is pumped mainly by the second-harmonic pulse of the neodymium lasers. The internal self-lasing problem is a disadvantage but it can be prevented by adding a black coating around the crystal. In the parametric amplification process, the energy in the pump beam is instantaneously transferred to the injection seed beam. Since there is no energy remaining in the crystal, there is no thermal lensing problem. On the other hand, since the temporal and spatial nonuniformity of the pump pulse is directly transferred to the input pulse, a complicated and expensive hardware system is required to manage the pulse. In addition, the limited temporal and spatial overlap reduces the amplification efficiency because the group velocity and direction of the input and pump pulses in the crystal are different. The angle of the pump and the input must be precisely adjusted to meet the phase-matching requirements of the broad frequency band. Lithium triborate, beta-barium borate, and potassium dihydrogen phosphate (KDP) crystals are often used. Stimulated-emission amplifiers and parametric amplifiers may be mixed in some cases.[7] Since deuterated KDP has already been developed for use as a frequency-conversion medium in laser fusion facilities, efforts are being made to utilize it for amplifying large-scale, high-energy broadband pulses.[8]

The spatial and temporal control of a pulse are important to provide the necessary experimental conditions. The focused beam intensity can be greatly increased by an adaptive optic system,[9] which consists of a deformable mirror and a feedback system connected to a wavefront sensor. The deformable mirror has a number of piezoelectric or mechanical actuators attached to the back side of the mirror substrate. The mechanical type has the advantage of maintaining the state even after the power is off. The quality of pulse compression can be similarly improved by controlling the spectral phase of the pulse. It is possible to remove the third-order dispersion by slightly adjusting the angle of the compressor, but the fourth- or higher-order terms can be removed by an acousto-optic programmable dispersion filter.[10] When the dispersion of the pulse is not spatially uniform, spatiotemporal coupling occurs at focus. The radial group delay in refractive image relays disperses the focus in the longitudinal direction and significantly reduces the intensity of the light. A diffractive lens has the opposite angular dispersion than a refractive lens and, therefore, can eliminate radial group delay.[4] Another application of the diffractive lens is "flying focus." The longitudinal chromatic aberration of the diffractive lens and the chirp of the pulse are combined to create the effect of longitudinal focal spot sweeping in time.[11] The efficiency of laser wakefield acceleration might be improved by this scheme. Another example of spatiotemporal effects is "wavefront rotation." This effect was used to isolate low-energy x-ray attosecond pulses.[12]

High-power lasers can generate secondary light sources/particles that can be used in medical, industrial, security, and pure scientific research, but they are less efficient than other alternatives because of their low repetition rate. To increase the repetition rate, the heat accumulation problem of the main amplifiers and the pump laser amplifiers must be solved (not for parametric amplifiers). For thin-disk Yb:YAG crystals used in pump lasers, a laser beam can be shined on one side of the disk and a cooling system can be attached to the other side to remove heat. Since the thickness is much thinner than the width, thermal gradients are formed only in the direction perpendicular to the surface, so that the lens effect of heat and polarization mixing is minimized. The thin-disk laser is used as a pump laser for the L1 optical parametric chirped-pulse–amplification laser at the ELI Beamlines Facility; it is aimed to supply pulses of 20 fs, 100 mJ at 1 kHz (Ref. 13). In large-scale petawatt lasers, the amplifier is stacked with several slabs and then cooled between the slabs by using room-temperature or low-temperature helium gas or water. The team at Lawrence Livermore National Laboratory has successfully constructed a 3.3-Hz petawatt laser based on this scheme [High-Repetition-Rate Advanced Petawatt Laser System (HAPLS)].[14]

Damage risk in the compressor remains the biggest concern for CPA. This risk is highest at the fourth grating, where the pulse is the shortest, because the damage threshold is lowered as the pulse becomes shorter. A multilayer dielectric grating was introduced to improve the damage threshold.[15] The uppermost layer is an etched dielectric grating, and a dielectric layer of high and low refractive indexes is repeatedly stacked under it for high reflectance. The damage threshold is improved by a factor of 10 (1 J/cm^2) compared to gold gratings, but the available bandwidth is narrow. To increase the bandwidth, a metal–dielectric grating has been considered with a dielectric top layer structure and metal layer at the bottom.[16] The thermal loading on gratings at a high repetition is another challenge.

We discuss applications in laser eye surgery and electron acceleration. Femotosecond lasers have been successfully used to cut out cornea flap in refractive surgery.[17] Femotosecond pulses provide better-controlled damage threshold. In electron acceleration, when a strong laser pulse focus passes through a plasma, the electrons are pushed out from focus by ponderomotive forces and a wakefield is formed in the ion density. When the electron is injected into the low potential of the ion wakefield, it moves with the wake as the pulse continues. Since this process occurs very quickly, the electrons accelerate to high energy. Lawrence Berkeley National Laboratory demonstrated 4.2 GeV using a microdischarge tube on the BELLA laser.[18]

CPA has revolutionized laser technology but it is also important to keep inventing new methods. For example, to overcome energy limitations, research is underway to amplify pulses using the Raman amplification phenomenon in a medium of plasma state.[19] In addition, efforts are being made to improve the system using new optical fibers and metamaterials. CPA opened the way for studying exciting advanced science in small laboratories. More commercialized petawatt lasers are becoming available in large laboratories and medical/industrial facilities.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

1. D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
2. E. B. Treacy, IEEE J. Quantum Electron. **QE-5**, 454 (1969).
3. J. Qiao *et al*., Opt. Express **15**, 9562 (2007).
4. J. Néauport *et al*., Appl. Opt. **46**, 1568 (2007).
5. O. E. Martinez, IEEE J. Quantum Electron. **QE-23**, 59 (1987).
6. G. Chériaux *et al*., Opt. Lett. **21**, 414 (1996).
7. L. Xu *et al*., Opt. Lett. **38**, 4837 (2013).
8. K. Ogawa *et al*., Opt. Express **17**, 7744 (2009).
9. N. Lefaudeux *et al*., Proc. SPIE **8600**, 86000W (2013).
10. P. Tournois, Opt. Commun. **140**, 245 (1997).
11. J. P. Palastro *et al*., Phys. Rev. A **97**, 033835 (2018).
12. F. Silva *et al*., Nat. Commun. **6**, 6611 (2015).
13. P. Bakule *et al*., Proc. SPIE **10241**, 102410U (2017).
14. T. M. Spinka and C. Haefner, Opt. Photonics News **28**, 26 (2017).
15. M. D. Perry *et al*., Opt. Lett. **20**, 940 (1995).
16. F. Canova *et al*., Opt. Express **15**, 15324 (2007).
17. T. Juhasz *et al*., Proc. SPIE **4633**, 1 (2002).
18. W. Leemans, Phys. Today **62**, 44 (2009).
19. V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. **82**, 4448 (1999).