Half of Nobel Prize in Physics honors the inventors of chirped pulse amplification

The laureates circumvented an intrinsic limitation in laser technology to develop an amplification protocol now found in nearly every high-power, ultrafast system.

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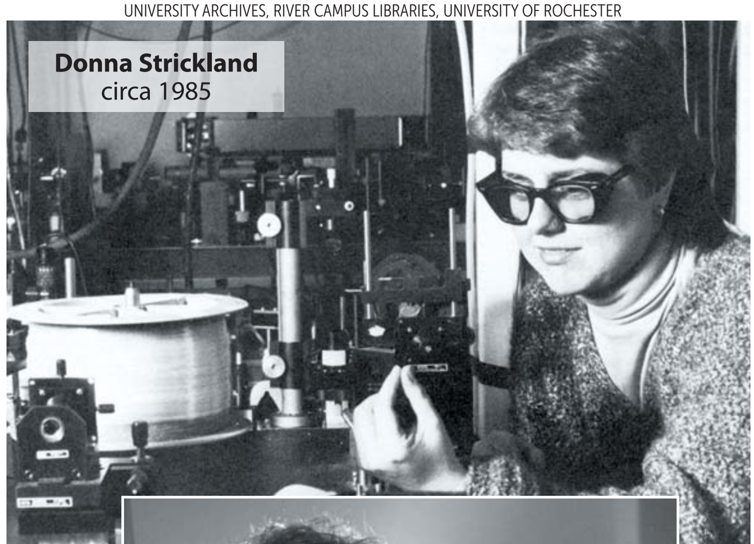
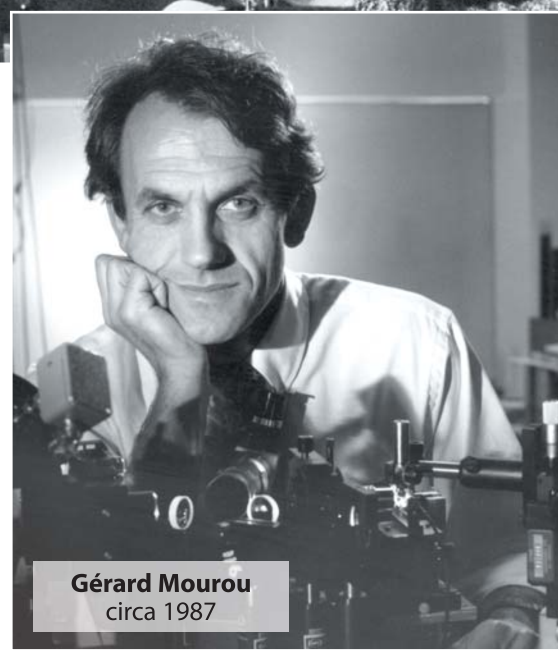


Donna Strickland
circa 1985



Gérard Mourou
circa 1987

By the mid 1960s, optical engineers had found multiple ways to intensify a laser's peak power by squeezing the pulse energy to durations as short as picoseconds. But those techniques had limits. If the light intensity inside a laser cavity grows too high, typically on the order of tens of gigawatts per square centimeter, it can exceed the dielectric breakdown threshold of the cavity's gain medium—just as lightning does in air—and fry it.

Dielectric breakdown isn't the only complication. A very intense laser pulse can also modify the medium's index of refraction, even to the point of producing a lens effect that forms a smaller pulse width. Known as Kerr focusing, the effect happens when a pulse is brighter in the center, as most are, than at the edges. As the beam tightens, it grows ever more intense until it ionizes the medium's atoms and spawns plasma filaments. The resulting distortions in the light pulse usually wreck the quality of its wavefront.

The problems caused the lasers' peak intensity to plateau at tens of gigawatts per square centimeter. The impasse was finally broken in the mid 1980s by a technique developed by graduate student Donna Strickland and her thesis adviser, Gérard Mourou, at the University of Rochester in New York. Called chirped pulse amplification (CPA), the technique does not amplify a short light pulse directly, but instead stretches it out by a factor of up to 10 000 in time, which reduces instantaneous power accordingly. In the dispersed, "chirped" state, the pulse can be safely amplified. Once outside the gain material, the pulse is then recompressed. (See the article by Mourou, Christopher Barty, and Michael Perry, PHYSICS TODAY, January 1998, page 22.)

For breaking the connection between a pulse's energy and the intensity to which it could be focused, the Nobel committee awarded Mourou and Strickland half of this year's Nobel Prize in Physics. It was the first time since Maria Goeppert Mayer's win 55 years ago that the prize was awarded to a woman. The brief, three-page paper that demonstrated the principle was Strickland's first publication.[1]

Chirped pulse amplification had a profound effect on subsequent laser development. "None of today's high-powered lasers would have been possible without it," says Wim Leemans, director of accelerator technology at Lawrence Berkeley National Laboratory. Just 10 years after CPA was developed, laser intensities reached 10^{20} W/cm^2. The electric field strength at that intensity is on the order of a teravolt per centimeter. That's 100 times the Coulomb field felt by a ground-state electron in the hydrogen atom.

From the microwave to the optical

In 1960 radio engineers had pulled off similar amplification with radar signals.[2] At the time, the trick was known as pulsed coding and compression; engineers sent microwave pulses through a positively dispersive delay line before amplifying and transmitting the longer-duration chirped pulses. Transmitting chirped pulses provided more accurate size and distance information from the reflected echoes.

In the early 1980s, Mourou recognized that adapting the technique to the optical regime would entail properly reconstructing the phases of much shorter wavelengths while compressing the pulse. Despite the challenge, Mourou was "comforted," he says, by the fact that the technique worked so well in the radio. Even so, when he asked his new student if she wanted to take on the project, "Donna was excited about it but also concerned that it might not be good enough for a Ph.D. thesis."[3]

Strickland says that the original plan for her PhD had been to measure the

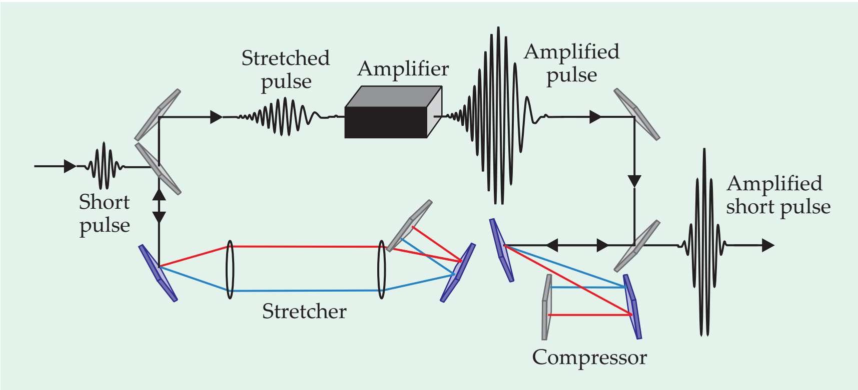


FIGURE 1. CHIRPED PULSE AMPLIFICATION. A short pulse is positively dispersed, or "chirped" in time, as it passes through a pair of diffraction gratings (purple). The stretched pulse is then amplified by as much as 11 orders of magnitude and recompressed as it passes through another, but negatively dispersive, pair of gratings. (Adapted from ref. 6.)

ninth harmonic of light from nickel plasmas. But that required higher intensities than existing dye-laser technology could muster. Out of necessity, her work shifted to the problem that had failed to interest her. Once it was solved, she resumed her work on multiphoton ionization. Her thesis eventually comprised CPA and multiphoton ionization of noble-gas atoms.

In their pivotal 1985 experiment that demonstrated the feasibility of CPA, Strickland used a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser to send a 150 ps, nanojoule pulse through 1.4 km of optical fiber whose refractive index was frequency dependent. A nonlinear optical effect known as self-phase modulation added yet more dispersion. The different frequency components traveled through the fiber at different speeds—with the red components moving faster than the blue ones—and the pulse quickly became spread out.

After amplifying the lower-energy-density pulse using a Nd:glass medium, Strickland then sent it through a pair of diffraction gratings, whose negative dispersion caused the blue components to catch up to the red ones. The recompressed pulse had an energy of about 2 mJ, a million times higher than it was originally, with a duration of a mere 2 ps.

The dispersive characteristics of the fiber differed from those of the gratings, however. The mismatch distorted the shape of the pulse, leaving it with wings on the edges. For Mourou, the mismatch became an obsession. While skiing with his wife at a resort near Rochester, he recalled the work of Oscar Martínez at the University of Buenos Aires. Martínez had found he could invert the sign of the phase shift imparted to an IR pulse simply by placing a telescope of magnification unity between a pair of diffraction gratings.[4] One could therefore dispense with optical fiber entirely; Mourou knew that all he needed were two pairs of diffraction gratings, the first with positive dispersion, to stretch the pulse, and the second with negative, to recompress it.

Mourou left the slopes right away, drove to the lab, and had his student Maurice Pessot drop what he was doing to work on the idea. Pessot confirmed Mourou's hunch and showed that an 80 fs pulse could be stretched by a factor of 1000 and compressed back to its original duration. Thirty years later, the matched grating-pair system is still part of the CPA architecture, as outlined in figure 1.

Shortly after Pessot's success, visiting scientist Patrick Maine integrated the grating pair into the Rochester group's first joule-scale amplifier system. One night in 1987, he, Strickland, Mourou, and others in the group threw an impromptu celebration after generating the first terawatt (10^{12} W) pulse from 1 J compressed into 1 ps. The achievement[5] inaugurated what's been dubbed the "tabletop terawatt."

From university to national lab

Early on, most CPA work was done using either mode-locked Nd:YAG lasers at

FIGURE 2. THE HIGH-REPETITION-RATE ADVANCED PETAWATT LASER SYSTEM is capable of producing 30 fs pulses with peak power of about 10^{15} W at 10 Hz. (Courtesy of Lawrence Livermore National Laboratory.)

1.06 μm or mode-locked dye lasers at 800 nm. Both types are sensitive to temperature changes and other environmental perturbations, which made them unstable and frustrating to use. That state of affairs changed in 1990 with the demonstration of the mode-locked titanium-doped sapphire laser by Wilson Sibbett and his group. Unlike dye, Ti:sapphire amplifies all the spectral components in pulses shorter than 5 fs. It also offers a much higher energy storage density than dyes. Peak laser powers can reach 10^4 times as high as those achievable using dye lasers of equivalent size.[6]

What's more, CPA could be adapted for use with large, expensive, and much higher-energy lasers. Even while Strickland was working with millijoule pulse outputs early on, Mourou realized that doped-glass laser systems already built for fusion experiments would deliver kilojoule energies. Nonetheless, it took another several years for researchers to reach intensities of 10^{15} W/cm^2. In 1997 Lawrence Livermore National Laboratory (LLNL) adapted CPA to its Nova laser system. Strickland worked there as a scientist in 1991 and 1992 and remembers a big push to build the large, flat diffraction gratings that could tolerate such bright light. The gratings had to be mounted in a vacuum chamber to avoid self-focusing in air.

The primary motivator behind the quest to reach ever-higher pulse intensities is the desire to transform materials, using shorter pulses, higher energies, or a combination of the two. A laser pulse's electric field scales as the square root of its intensity and exerts a force on all charged particles. The force can approach or exceed the force that binds electrons to atoms or atoms to molecules. In short, by controlling the light, one controls the material. Possibilities abound: accelerating particles, dissociating molecules, triggering a reaction, drilling holes, and numerous others. Many can be achieved using tabletop lasers, thanks to CPA.

In 1990, a year before Strickland headed to LLNL, Mourou founded the Center for Ultrafast Optical Science at the University of Michigan, where LASIK (laser-assisted *in situ* keratomileusis) eye surgery was developed. Since then, femtosecond lasers have become routinely used as high-precision subsurface scalpels in treating myopia, astigmatism, and other medical conditions. The ultrashort pulses in the IR precisely cut away a flap from the cornea by creating a hot plasma whose shock wave expands so quickly that it cleaves away material without leaving debris or heating surrounding tissue.

High harmonics and laser wakefields

Visible or IR femtosecond pulses can be converted into even shorter bursts of coherent soft x rays using high-harmonic generation (HHG). For the conversion to occur, the original pulses have to be powerful—1 mJ or more—and ultrashort. HHG only happens when an intense laser field pulls an electron away from a molecule in a fraction of one optical cycle and sends it crashing back into the molecule when the field reverses during the next half cycle.

The energy dissipated in each crash is converted into a single photon whose duration can be as short as attoseconds. That time scale is almost inconceivably brief, roughly the time it takes light to traverse a water molecule. (See PHYSICS TODAY, April 2003, page 27, and the article by Henry Kapteyn, Margaret Murnane, and Ivan Christov, PHYSICS TODAY, March 2005, page 39.)

Within the past decade, optical scientists have been striving to develop laser technology that makes particle accelerators far more compact and economical than conventional RF linacs, which are kilometers long. One approach, laser wakefield acceleration, was proposed nearly 30 years ago by Toshiki Tajima and John Dawson at UCLA and is currently being studied at the BELLA petawatt laser at Lawrence Berkeley National Laboratory.

The idea in wakefield acceleration is to use a plasma of ionized helium to transform the energy from BELLA's laser pulse into the kinetic energy of accelerated electrons. The radiation pressure from a pulse fired into the plasma moves the electrons out of the way while the ions barely move. Electrostatic forces then pull the electrons and ions back together. The resulting pattern of alternating positive and negative charges, known as a laser wake, supports a large electric field. (See the article by Wim Leemans and Eric Esarey, PHYSICS TODAY, March 2009, page 44.)

For typical plasma densities, BELLA produces accelerating electric fields up to 1 GV/cm. That's three orders of magnitude higher than conventional RF technology. So to reach a given electron energy, a laser-plasma accelerator could be one thousandth the length of its conventional RF counterpart.

ELI and particles out of the vacuum

The peak power of a petawatt laser is many times greater than the combined output of every power station on Earth. Pulses that deliver such prodigious power, if only for an instant, create environments in the laboratory suitable for studying matter at extreme conditions, such as inside stars or close to the event horizon of a black hole. (See the article by Paul Drake, PHYSICS TODAY, June 2010, page 28.)

The highest intensity one can reach today is on the order of 10^{22} W/cm^2, high enough to accelerate electrons to relativistic speeds but not high enough to drive nonlinear quantum electrodynamics or nuclear-physics experiments. The cutting-edge system that LLNL recently built, shown in figure 2, operates at 10 Hz, which will be a world record when the laser demonstrates its design goal of 1 PW. Delivered this past June to the European Union's Extreme Light Infrastructure (ELI) facility in the Czech Republic, the laser may help breach even higher intensity regimes.

As Stanford University's Philip Bucksbaum points out, the capability exists to raise laser intensities another nine orders of magnitude. That milestone will be accomplished, he predicts, using a CPA-based petawatt laser in tandem with an electron beam such as the one at SLAC or at DESY in Hamburg, Germany. When laser pulses are slammed into the electron beam, their intensity in the electron's frame of reference will be boosted by a value of $4\gamma^2$, where γ is the relativistic Lorentz factor, $(1-v^2/c^2)^{-1/2}$, with v the beam velocity and c the speed of light. When the intensity of light in the boosted frame reaches 4×10^{29} W/cm^2, the stability of the vacuum itself breaks down, and dense clusters of electron and positron pairs are expected to appear *ex nihilo*.

About the laureates

Gérard Albert Mourou was born in 1944 in Albertville, France, and obtained his PhD from Pierre and Marie Curie University (now part of the Sorbonne University group) in Paris in 1973. He did a postdoc at the University of California, San Diego, and spent three years at École Polytechnique in Palaiseau. He became a professor at the University of Rochester in New York in 1977 and was a founding director in 1991 of the Center for Ultrafast Optical Science at the University of Michigan, where he taught for more than 16 years. In 2007 he initiated the Extreme Light Infrastructure project, which consists of high-power laser facilities in the Czech Republic, Romania, and Hungary. He is a professor at École Polytechnique and an amateur music composer and filmmaker.

Donna Theo Strickland was born in 1959 in Guelph, Ontario, Canada, and obtained her PhD in optics from the University of Rochester in 1989 under Mourou's supervision. From 1988 to 1991 she was a research associate at the National Research Council of Canada, where she worked with Paul Corkum on ultrafast phenomena. After a stint at Lawrence Livermore National Laboratory in 1991–92, she joined Princeton University's Advanced Technology Center for Photonics and Optoelectronic Materials. In 1997 she became the second female professor of physics at the University of Waterloo. In 2013 she served as president of the Optical Society.

Mark Wilson

References

1. D. Strickland, G. Mourou, *Opt. Commun.* **56**, 219 (1985).
2. J. Klauder et al., *Bell Syst. Tech. J.* **39**, 745 (1960).
3. G. Mourou, in *A Jewel in the Crown: Essays in Honor of the 75th Anniversary of the Institute of Optics of the University of Rochester*, Meliora Press (2004), p. 275.
4. O. E. Martínez, *IEEE J. Quantum Electron.* **23**, 1385 (1987).
5. P. Maine et al., *IEEE J. Quantum Electron.* **24**, 398 (1988).
6. S. Backus et al., *Rev. Sci. Instrum.* **69**, 1207 (1998).