

# Ultrafast Lasers Open New Doors

FEATURE

by Eric J. Lerner

Femtosecond lasers herald a new age of investigation and application

The production of pulses of radiation only femtoseconds long, often consisting of merely a few oscillations and typically at extremely high intensity, has become almost a commonplace activity in hundreds of small- and medium-sized research laboratories around the world. Relatively inexpensive, compact tabletop laser systems are now generating pulses that are shorter and more intense than those generated only at the largest government laboratories just a few years ago. And just as the world of computing was transformed two decades ago with the advent of personal computers, the small but extremely powerful ultrashort-pulse laser systems are beginning to make an impact in a great many research fields.

These areas range from the study of biochemical reactions, to fundamental studies of the laws of quantum mechanics, to explorations of strange phenomena such

as superluminal velocities, which appear to be greater than the speed of light in a vacuum.

Beyond these areas of active work, ultrashort pulses are finding potential applications in biomedicine, where short pulse times minimize heating of adjacent tissues and could

allow more precise microsurgery; in micromachining; and in optical spectroscopy. The next few years are likely to see this new tool become a workhorse in laboratories, hospitals, and factories (Figure 2).

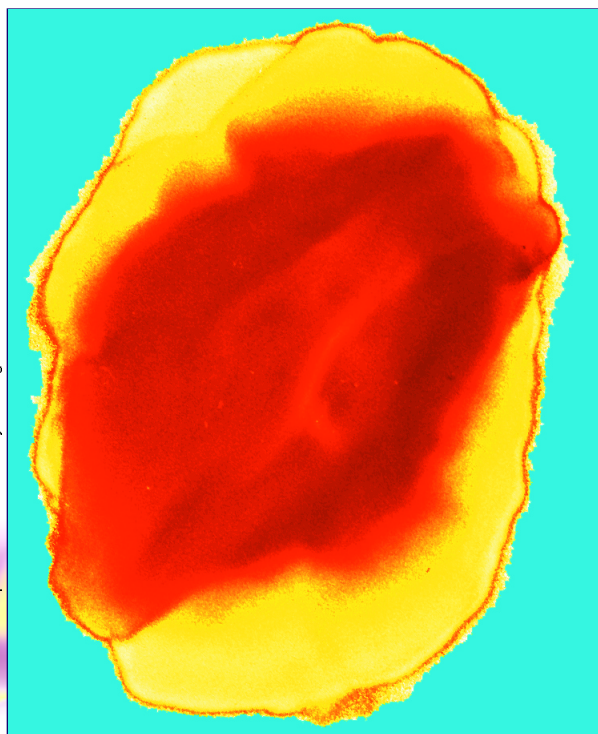
Since 1987, when the current methods of compressing laser pulses were first developed, the maximum intensity of laser pulses—the concentration of power per unit area—has doubled every few months and increased a millionfold over a decade, with no limit yet approached. Ultrafast lasers can now deliver pulses shorter than 5 fs, which equals only a couple of oscillations of light. Peak powers have exceeded 1,300 TW, with an intensity on targets of  $10^{21}$  W/cm<sup>2</sup>. This is the equivalent of focusing the power of all the sunlight falling on earth onto a spot 0.1 mm on a side.

Such intense radiation can accelerate electrons to near the speed of light, generate pressures hundreds of times greater than those at the center of the earth, and create magnetic fields a billion times greater than Earth's. In these extreme conditions, researchers can probe the behavior of matter at high energy and test theories in fields ranging from astrophysics and general relativity to quantum mechanics. Conceivably, such pulses may be the way to provide very compact particle accelerators or even generate fusion energy.

What is perhaps equally exciting is that, like computer circuits, high-power lasers have shrunk dramatically in the last decade in both cost and size. Some lasers capable of extremely high performance can fit on a tabletop and be built for less than \$1 million, well within the reach of industrial research centers and small laboratories at universities and hospitals. Experiments that previously might be contemplated only at large facilities and cost millions of dollars now can be performed by small teams at dozens of facilities.

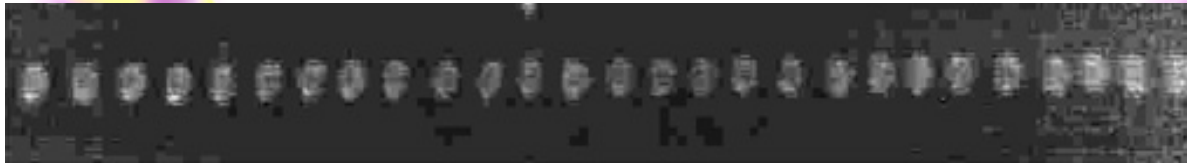
## Chirped-pulse amplification

The key to this rapid advance was the development in the late 1980s of chirped-pulse amplification, or CPA. Before then, material properties appeared to limit the intensity that laser pulses could reach. Because the index of refraction varies linearly with intensity, at intensities of gigawatts per square centimeter a beam that is more intense in the center is affected by a high index of refraction at the center, which creates a lens and thus disrupts the beam. Given this intensity limit, short-pulse production required using materials with a low energy density, such as dyes and excimers, with energy densities of only



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Figure 1. Image of a proton beam as a high-intensity tabletop laser strikes a 1.8- $\mu$ m-thick aluminum foil, accelerating ions in almost a million times shorter distance than a cyclotron.



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millijoules per square centimeter. This, in turn, meant that lasers with any respectable energy output had to be large and expensive.

The breakthrough came with CPA, in which a short-duration, low-energy pulse is produced and then stretched out in time, amplified, and recompressed. Originally, this technology was developed for radar, but it translated well into the optical regime. In CPA, a very short pulse, with very little energy—at a level of nanojoules—is generated by a suitable laser and optimized to generate a short pulse, not peak power. In fact, peak power at this point is less than 1 MW. The pulse is then put through a stretcher—two antiparallel diffraction gratings connected by a telescope with a magnification of 1, which yields an image the same size as the object. The longer the wavelength of light, the shorter the path the waves travel and thus the sooner they arrive at the next stage. The result is an extension of the pulse from as little as 5 fs to as much as a nanosecond, a stretching by a factor of more than  $10^5$ .

The pulse, now with perhaps less than 1 W of power, is fed into a high-energy-density medium, such as Ti:sapphire, which amplifies the pulse 10 billionfold or more, up to the several-gigawatt limit imposed by nonlinearities. However, this limit is far surpassed when the amplified pulse is recompressed by a pair of parallel gratings, with the path length shortest for short wavelengths, a reversal of the stretching process. With the pulse recompressed back to a few femtoseconds, peak powers of petawatts ( $10^{15}$  W) can be achieved.

More than higher power is achieved with CPA because of the use of high-energy-density materials. With energy densities thousands of times greater than those of dye lasers, CPA lasers can be thousands of times more compact for the same energy output, making possible benchtop terawatt lasers. In addition, pulse stretching and compression are added before and after the main amplification stage, so CPA lasers can be back-fitted to existing high-power lasers at a relatively small expense, thus converting terawatt lasers such as NOVA at Lawrence Livermore National Laboratory to petawatt lasers with subpicosecond pulses.

For CPA to work, the spectrum after amplification must be exactly the same as that before, or the compressed pulse will be longer than the initial pulse. Because an ultrashort pulse must have a broad bandwidth, this requires the amplification medium to have an equally broad bandwidth with a flat response that ampli-

fies high and low frequencies by the same amount over the entire width. For example a 5-fs pulse requires a bandwidth of nearly 200 nm centered at the 800-nm wavelength. Fortunately, there is one solid-state material with high energy density that has such a huge bandwidth—Ti:sapphire, with a bandwidth extending from 700 to 1100 nm.

In a typical terawatt system, a Ti:sapphire laser pumped by an argon-ion laser generates a seed pulse that is fed into the pulse stretcher and a two-stage Ti:sapphire amplifier, each pumped by a single Nd:YAG laser. To achieve the shortest pulses with the least dispersion, physically short crystals are used, generally only a few millimeters in length. The pulse compressor of this system then produces a 3-TW, 70-mJ, 25-fs pulse that can be repeated at a rate of 10 Hz. Other systems can produce 5-fs pulses.

## Compact X-ray sources

Among the many areas of research made possible by ultrashort laser pulses, one of the most active is the effort to develop compact X-ray lasers and other sources of coherent X-rays. Combining the high spatial resolution of X-rays with the high time resolution of ultrashort pulses provides a tool for investigating fast phenomena at the molecular level, including the details of biochemical processes within living cells. This could allow pharmaceutical investigators to observe a new drug during a biochemical reaction.

In the past year or so, several teams of researchers have shown that it is possible to generate coherent fast X-ray pulses by reflecting ultrashort laser pulses from the boundary between a plasma and a vacuum. The production of X-rays occurs through the interaction of visible photons with relativistic electrons in the plasmas. The photons are Doppler-shifted by the electrons, producing a spectrum of higher harmonics with wavelengths down to 20 nm or shorter. The femtosecond pulses themselves produce a relativistic plasma at intensities of more than  $10^{18}$  W/cm<sup>2</sup>. At the Laboratory of Applied Optics (Palaiseau, France), for example, 35-fs laser pulses focused on a glass target produced up to the 35th harmonic. The beam of each harmonic diverges no more than the incoming laser beam.

While coherent X-rays can be produced at energies of up to 0.5 keV, incoherent bursts of X-rays can extend to much higher energies. At laser intensities from  $2 \times 10^{18}$  to  $10^{19}$  W/cm<sup>2</sup>, electrons can be heated to several hun-

Figure 2. This image of the damage caused by an 80-fs laser on plasma demonstrates why ultrafast lasers can be used for surgery, as precise cuts can be made with little collateral damage.



Figure 3. Electro-optic sampling combines ultrafast laser pulses and novel optoelectronic devices to generate and measure electrical pulses of the shortest possible durations.

dred kiloelectron volts (several billion degrees Celsius), emitting continuum bremsstrahlung radiation as they interact with ions. When Ting Guo and his colleagues at the University of California, San Diego, focused their tabletop, 28-fs, 80-mJ pulses at a moving copper wire, they inferred a 300-keV electron temperature from the X-ray spectrum measured with a scintillation detector (Figure 5).

With the most tightly focused spots, temperatures approached 1 MeV. In addition, the electrons generated line radiation at 8 keV. Such single-frequency radiation, even if incoherent, can be important in X-ray diffraction studies of fast chemical reactions, in which a small-size X-ray source is needed. With this technique, source size is essentially the same as that of the laser spot—only a few micrometers across. Guo is constructing a similar X-ray system, but with a higher repetition rate, at the University of California, Davis, and he will use this source to study ultrafast phase transitions and the self-assembly of excited species.

## Fast lasers, fast ions

Ultrashort laser pulses can accelerate ions as well as electrons to high energies, a process of interest both for thermonuclear fusion research and for efforts to develop compact particle accelerators. Using lasers at the relatively modest intensity of  $3 \times 10^{16}$  W/cm<sup>2</sup>, a research collab-

oration between the Institute of Plasma Physics and Laser Microfusion (Warsaw, Poland) and the Institute for Laser Physics (St. Petersburg, Russia) measured the energy of the ions ejected from a copper target. They found that the ions fell into two sharply differentiated groups, a larger one with a velocity of around 740 km/s and a smaller one with a velocity of 2,700 km/s, which correspond to maximum energies of 29 and 150 keV, respectively. Such high energies are sufficient to induce fusion reactions in a variety of fuels.

Although focusing a pulse on a solid target accelerates ions by thermal processes, in other cases the huge electrical fields generated by ultrashort pulses also increase ion speed (Figure 1). Researchers at the University of Michigan's Center for Ultrafast Optical Science (Ann Arbor, MI) focused 400-fs, 6-TW lasers to an intensity of  $6 \times 10^{18}$  W/cm<sup>2</sup> within a supersonic helium gas jet. The laser pulse self-focused itself further as it moved through the

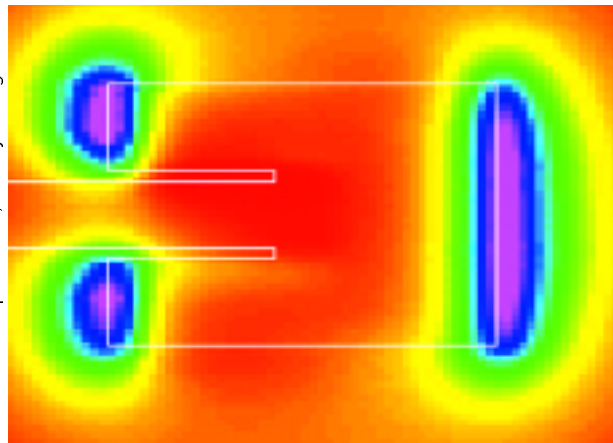


Figure 4. An ultrafast laser can be used to image the electric field distributions above complex microwave circuits, such as this "three-fingered" antenna, measuring three field components in three dimensions.

gas, creating a long narrow channel. This occurred as the laser pulse expelled electrons from the channel, at the same time accelerating them to relativistic velocities, which created an optical lens out of the plasma. As the electrons left the channel, a strong electric field built up that accelerated the ions, which followed the electrons out of the channel. The result is the acceleration of 500-keV ions with relatively high efficiency: in fact, nearly 5% of the laser-pulse energy is converted to fast-ion energy.

At this center, several other fields of research are also benefitting from the use of ultrafast lasers (Figures 3 and 4).

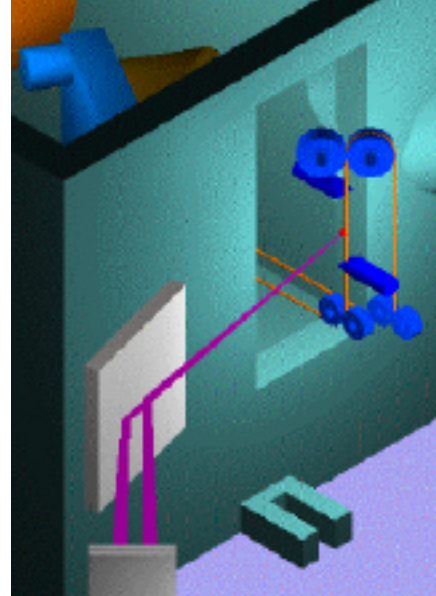
One of the most exotic applications of ultrashort pulses is in the study of superluminal propagation—velocities that are apparently faster than  $c$ , the velocity of light in a vacuum. Although superluminal velocities for matter or energy transfer are prohibited by special relativity, a pulse peak can exceed this velocity in certain circumstances, and has actually been observed to do so. Typically, this phenomenon involves tunneling or evanescent waves produced in situations in which the pulse decays

Figure 5. In this rendering, a focused ultrafast laser (red dot) strikes a moving copper wire (orange) fed from a vacuum chamber (green) through three pairs of guiding bearings (blue) and between a pair of stabilizers (blue) to generate X-rays (purple).

exponentially rather than oscillates. According to theory, tunneling speed or evanescent wave propagation should exceed  $c$ . But the ability of the pulse peak to exceed  $c$  does not mean that energy, and thus information, can travel faster than  $c$ ,

and thus violate special relativity.

To study this phenomenon, ultrashort pulses are needed because the time delays involved are so small, generally at the femtosecond level. The development of femtosecond terahertz pulses in the far



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infrared has enabled several such studies, some of which gave surprising results. Klaas Wynne and colleagues at the University of Strathclyde (Glasgow, Scotland) have performed experiments with frustrated total internal reflection, in which total internal reflection light is completely reflected from a prism surface or other reflecting surface. But when another prism is brought close to the surface, some light leaks out through an evanescent wave, producing what is called frustrated total internal reflection.

Wynne's team sent a single-cycle terahertz pulse through an air gap between two prisms. Measurements showed that the pulse crossed the gap with essentially zero time delay, moving more than a pulse-width ahead of a pulse traveling at  $c$ . This result implied that some energy actually exceeded the speed of light, thus violating special relativity. However, Wynne believes that further analysis will show that the phenomenon cannot be used to transmit information faster than the speed of light and therefore is not a true violation. Research in this hot field is continuing at a rapid pace, and more sophisticated tests of the predictions of both special relativity and quantum mechanics will take place in the near future.

### For further reading:

Badziak, J., et al. *Lasers and Particle Beams* 1999, 17, 323.

Tarasevitch, A., et al. Proc. Quantum Electronics and Laser Science Conf. May 1999, p 93.

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