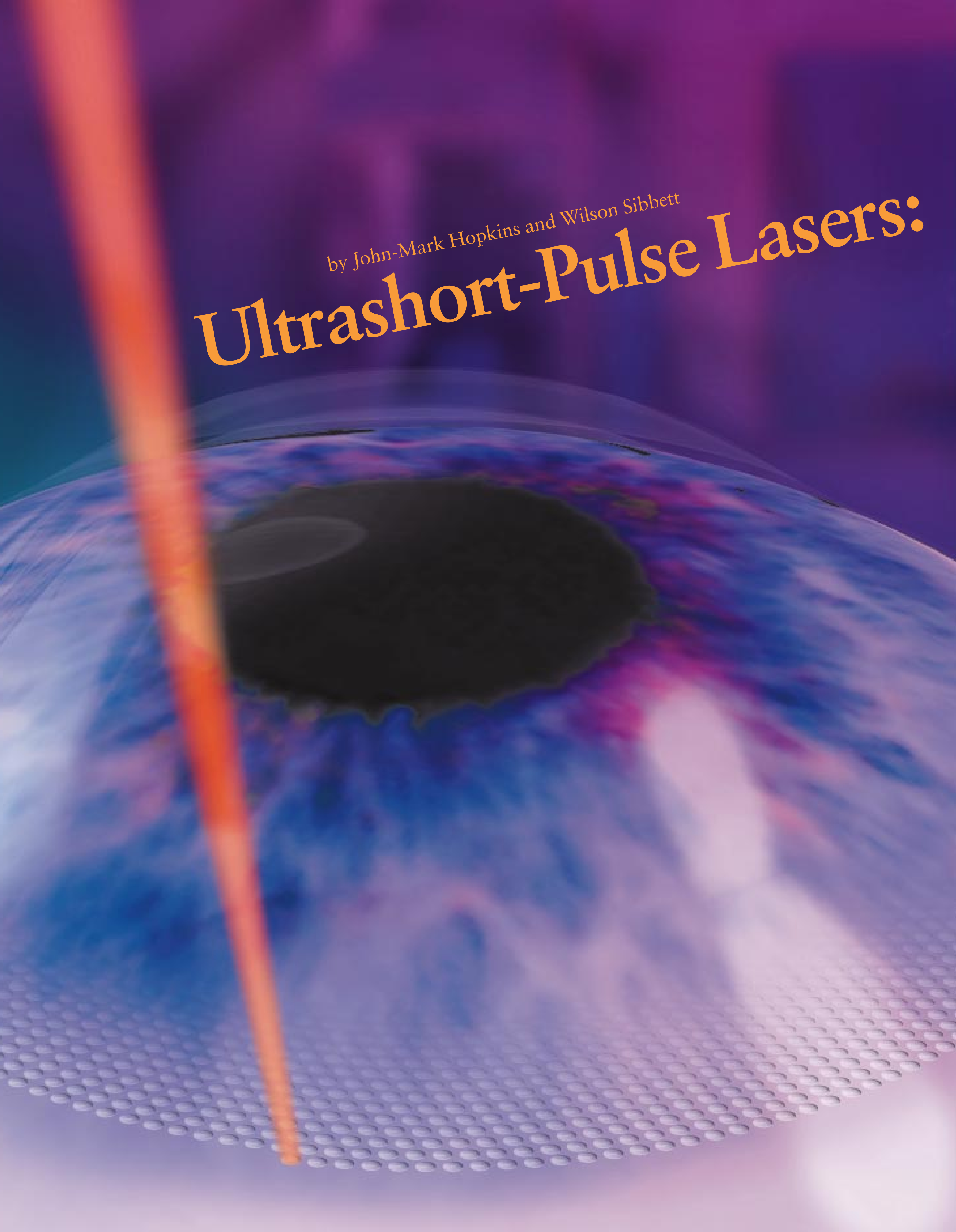


Ultrashort-Pulse Lasers:

by John-Mark Hopkins and Wilson Sibbett

Big Payoffs in a Flash

The briefest man-made events, pulses of laser light lasting millionths of a nanosecond, can be used for delicate eye surgery, high-bandwidth communications and stop-motion studies of molecules reacting

How long did it take you to read this sentence? Just recognizing the first letter took only milliseconds. Around 0.05 millisecond, or 50 microseconds, passes each time chemicals diffuse across a synapse, carrying a signal from one neuron to another in your brain. Are you holding the magazine at a comfortable reading distance? It takes light one or two nanoseconds to travel from the page to your eye and about 20 picoseconds to pass through the lens in your eye. And yet these brief natural events are epically long compared with the shortest man-made events, which proceed 1,000-fold more swiftly: pulses of laser light that last for only a few femtoseconds (quadrillionths of a second).

It is hard to comprehend the brevity of a femtosecond (10^{-15} second). One femtosecond is to one second as one second is to 32 million years. Put another way, more than 10 times as many femtoseconds elapse every second than hours have passed since the big bang! Some of the most fundamental processes in the universe—for example, electrons moving between atoms and molecular bonds breaking or forming—occur on timescales of hundreds of femtoseconds or less. Scientists have used femtosecond pulses to record and study such fast events in detail, much as Harold E. Edgerton of the Massachusetts Institute of Technology used microsecond flashes of light to produce unforgettable photographs of splashing droplets and flying bullets. The pioneering work of Ahmed H. Zewail of the California Institute of Technology enabled chemists to see how reactions proceed on timescales of a few hundred femtoseconds, earning him the Nobel Prize in Chemistry [see "The Nobel Prizes for 1999," Scientific American, January]. Researchers have also effectively "freeze-framed" the dynamics of electrons within semiconductor materials to enable them to design better optoelectronic devices to achieve the ever faster signal processing demanded by the computer and telecommunications industries.

The science and technology of ultrashort-pulse lasers have enjoyed much exciting progress since they were developed in the mid-1960s. In particular, the past decade has seen pulses shorter than 10 femtoseconds and the emergence of a new generation of versatile, compact ultrashort-pulse lasers—a revolutionary change from their large, temperamental, power-hungry ancestors. Such laser designs, which make use of sophisticated nonlinear optical phenomena and concurrent advances in diode lasers, increasingly meet the stringent specifications and reliability necessary for many industrial and medical applications. As we enter the 21st century, ultrashort-pulse lasers are becoming more impressive in scope and intensity, producing beams that span the electromagnetic spectrum from x-rays to T-rays (terahertz radiation, beyond infrared) and generating optical peak powers as colossal as petawatts (billions of megawatts). As a result, many new applications in physics, chemistry, biology, medicine, and digital optical technology are emerging and attracting worldwide interest in science and industry.

ULTRASHORT LASER PULSES can slice a flap of the cornea for LASIK eye surgery by producing a layer of perforations at a constant depth. The holes would be smaller and the beam more tightly focused than in this artist's depiction.

SLIM FILMS

Sharpest of Scalpels

Many applications of ultrashort-pulse lasers make use of the very high power that each pulse momentarily provides. Although the average power from the laser may be quite moderate and the total energy within a pulse small, the extremely short duration of each pulse guarantees that the peak instantaneous power is large. In a typical system the interval between pulses is 100,000 times longer than the pulses themselves, and so the peak power is about 100,000 times the average power. For example, a 100-femtosecond pulse with a moderate energy of three microjoules (not enough energy to heat a drop of water by a millionth of a degree Celsius) delivers a peak power of 30 megawatts.

When focused on a tiny spot, such high powers ablate many materials, making ultrashort pulses a tool for micromachining, drilling, cutting and welding. Precision can exceed the beam focus if the pulse intensity is carefully set so that only the brightest central part of the beam rises above the material's ablation threshold. The pulse deposits the energy at the focus too rapidly for the heat to diffuse into the surrounding unirradiated areas, ensuring smooth and precise features [*see top illustration on page 75*]. Researchers have demonstrated this technique by accurately machining diamond, titanium carbide and tooth enamel. Amazingly, the lasers can even slice safely through high explosives—they vaporize what is at the cutting point without detonating the adjoining material. This procedure may prove practical in the decommissioning of weapons.

Surgical applications also abound. For example, in microvascular surgery an ultrashort-pulse laser can drill small holes in the walls of the heart to supply oxygenated blood to cardiac muscles with irreparably blocked blood vessels. Ul-

The Basics

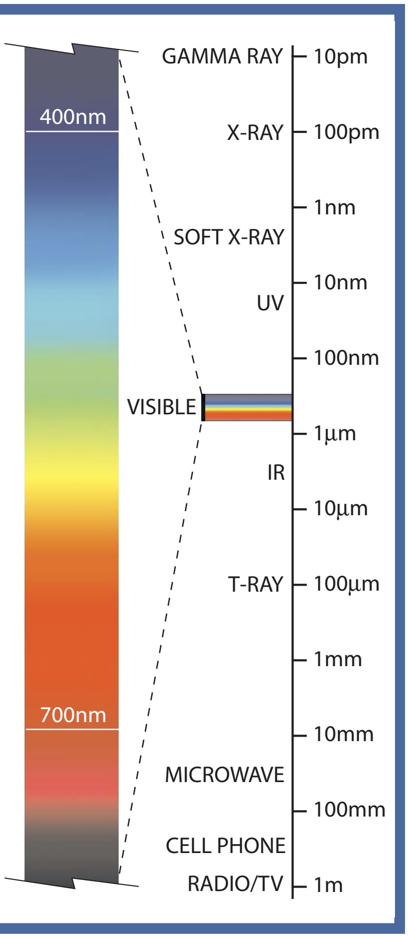
Electromagnetic radiation has a thousand faces. Most familiar is visible light. All the colors of the rainbow are distinguished by one property, the light's wavelength, ranging from about 380 nanometers (nm) for the deepest perceivable violet to about 750 nm for the reddest of reds. Most of the colors we see around us, particularly the browns, grays and pastels not found in a rainbow, involve a mixture of many different wavelengths. The electromagnetic spectrum extends far beyond visible light, to gamma rays at the short-wavelength and high-frequency extreme, and radio waves at the other. The mild waves emitted by 60-hertz household wiring would lie about seven divisions below the lowest mark on the chart at the right.

Distinctions of wavelength are just the beginning of how light can be packaged. Most light is incoherent, analogous to a stadium crowd roaring. Lasers produce coherent light—the crowd sings a song in unison. Light can come in continuous waves, like breakers endlessly arriving at the beach, and also as a pulse, like a tsunami. Compressing light into the shortest of coherent pulses—the record stands at around four femtoseconds—creates an extraordinarily versatile tool with a remarkable combination of power and delicacy.

News stories on other gymnastics and mysteries of electromagnetic radiation appear on pages 20 and 26 of this issue. *—Graham P. Collins, staff writer*

Small and Large

Prefix	Factor	Name (U.S.)	Prefix	Factor	Name (U.S.)
milli (m)	10^{-3}	thousandth	kilo (k)	10^{3}	thousand
micro (µ)	10^{-6}	millionth	mega (M)	10^{6}	million
nano (n)	10^{-9}	billionth	giga (G)	10^{9}	billion
pico (p)	10^{-12}	trillionth	tera (T)	10^{12}	trillion
femto (f)	10^{-15}	quadrillionth	peta (P)	10^{15}	quadrillion
atto (a)	10^{-18}	quintillionth	exa (E)	10^{18}	quintillion
zepto (z)	10^{-21}	sextillionth	zetta (Z)	10^{21}	sextillion
yocto (y)	10^{-24}	septillionth	yotta (Y)	10^{24}	septillion



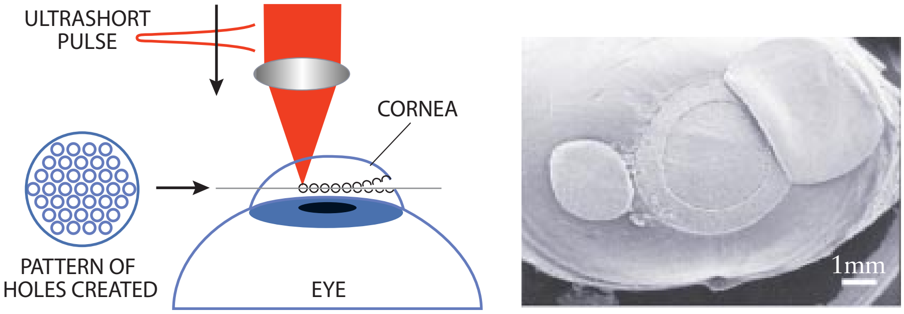
LAURIE GRACE

trashort pulses are especially effective because their low average power reduces the collateral tissue damage. Scientists at Lawrence Livermore National Laboratory have used ultrashort pulses, with a clever monitoring system, to remove bony intrusions into the spinal column without damaging the adjacent nerve tissue. And researchers at the University of Michigan and the University of Heidelberg in Germany have demonstrated a remarkable form of eye surgery: a beam of ultrashort pulses focused to an exact depth in the cornea create a small mesh of interconnecting bubbles, or cavitations [*see illustration below*]. A flap of the cornea can then be peeled back, exposing a disk of the lower tissue for removal. The top layer is then put back, smooth surface intact, and the resultant flattening of the cornea corrects myopia, or nearsightedness. The laser cuts a smoother flap than the standard knife-based technique and provides more control over the cut's shape and location.

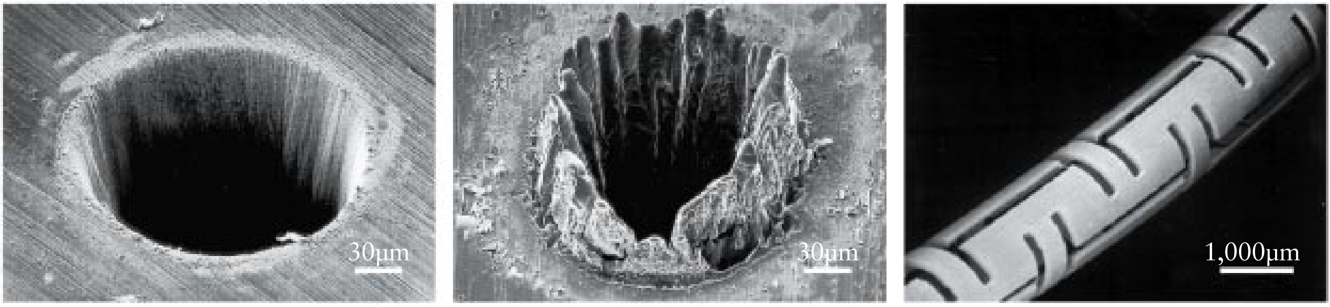
Imaging

An obvious use for any new source of light is to produce images in novel ways. In biology and medicine, imaging often relies on special dyes or natural molecules in tissues fluorescing in response to short-wavelength light, such as violet light. Usually this proceeds by a molecule absorbing a single quantum of light, or photon, and subsequently emitting another photon. Using light of longer wavelength would have many advantages, but such photons carry less energy, so two or more photons must act in synchrony to excite each molecule. This multiphoton excitation becomes significant only at very high intensities. Ultrashort pulses provide the required intensities while delivering sufficiently low average power to avoid tissue damage. In addition, longer-wavelength light penetrates tissues more efficiently and causes less damage to cells than the shorter wavelengths. The intensity can be adjusted so that fluorescence occurs predominantly at the focus of the beam,

EXPERIMENTAL laser eye treatment detaches a flap of the cornea by punching tiny holes at the focus of the laser (*left*). Further such cuts detach a subsurface disk of the cornea (*right*). When the flap is laid back, the cornea is flattened, correcting myopia. In conventional LASIK surgery, the flap is cut with a blade—a riskier procedure that produces a rougher cut.



LAURIE GRACE (*left*); GÉRARD A. MOUROU *University of Michigan* (*right*)



HERBERT WELLING *Laser Zentrum Hannover*

LASER MICROMACHINING benefits from the properties of the shortest pulses. A 200-femtosecond pulse produces a very smooth hole in steel by ablation (*left*). Pulses of half the power and lasting 16 times longer melt the surrounding areas (*center*) unless special techniques are used. Laser micromachining can produce smooth tantalum stents (*right*) used to treat cardiovascular problems.

resulting in a much higher resolution [*see illustration below*]. This technique, introduced by Watt W. Webb of Cornell University, produces three-dimensional images of living tissue with better clarity and definition than were possible before. A related method images silicon microchips through their plastic packaging by detecting electric currents induced by multiphoton excitations.

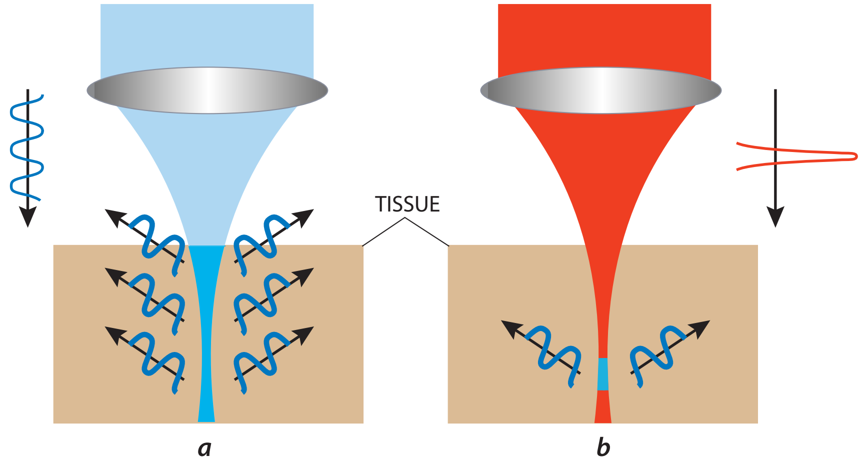
Another new form of imaging is T-ray imaging, which uses radiation from the terahertz part of the electromagnetic spectrum. This region, corresponding to wavelengths from 15 microns to one millimeter, lies on the long-wavelength side of the infrared. T-rays can penetrate deeply through many materials that are opaque to shorter wavelengths, such as visible light. In fact, many common materials are relatively transparent to terahertz radiation. Conversely, T-rays can achieve images with finer resolution than is possible with microwaves, which have wavelengths of about a centimeter and up.

In the 1980s David Auston and his coworkers at Columbia University managed to create T-rays by firing ultrashort pulses at specially tailored semiconductor structures. The pulses induce flows of electrons that in turn generate the T-rays. T-rays produced by laser pulses are easier to separate from background radiation and noise and can distinguish layers of very similar material, such as those of different types of soft tissue. For example, T-ray imaging can clearly distinguish between burned and healthy tissues. First demonstrated by Martin Nuss and his colleagues at AT&T Bell Laboratories (now Lucent Technologies) in 1995, terahertz-pulse imaging is still in its infancy, but researchers have applied it to inspect electronic components and to detect the earliest stages of tooth decay and other diseased tissues. At airports, T-rays might be an effective way to detect ceramic weapons, which are difficult to identify using standard x-ray equipment.

In industry, ultrashort-pulse lasers are proving invaluable for making accurate measurements during the manufacture of highly complex microchips. They monitor the thickness of metal and semiconductor layers without interrupting production, resulting in more efficient fabrication [see "Picosecond Ultrasonics," by Humphrey Maris; Scientific American, January 1998]. Another possible commercial application is in telecommunications: in 1997 Nuss and his co-workers at Lucent showed how to use femtosecond pulses to transmit more than 200 data channels through an optical fiber.

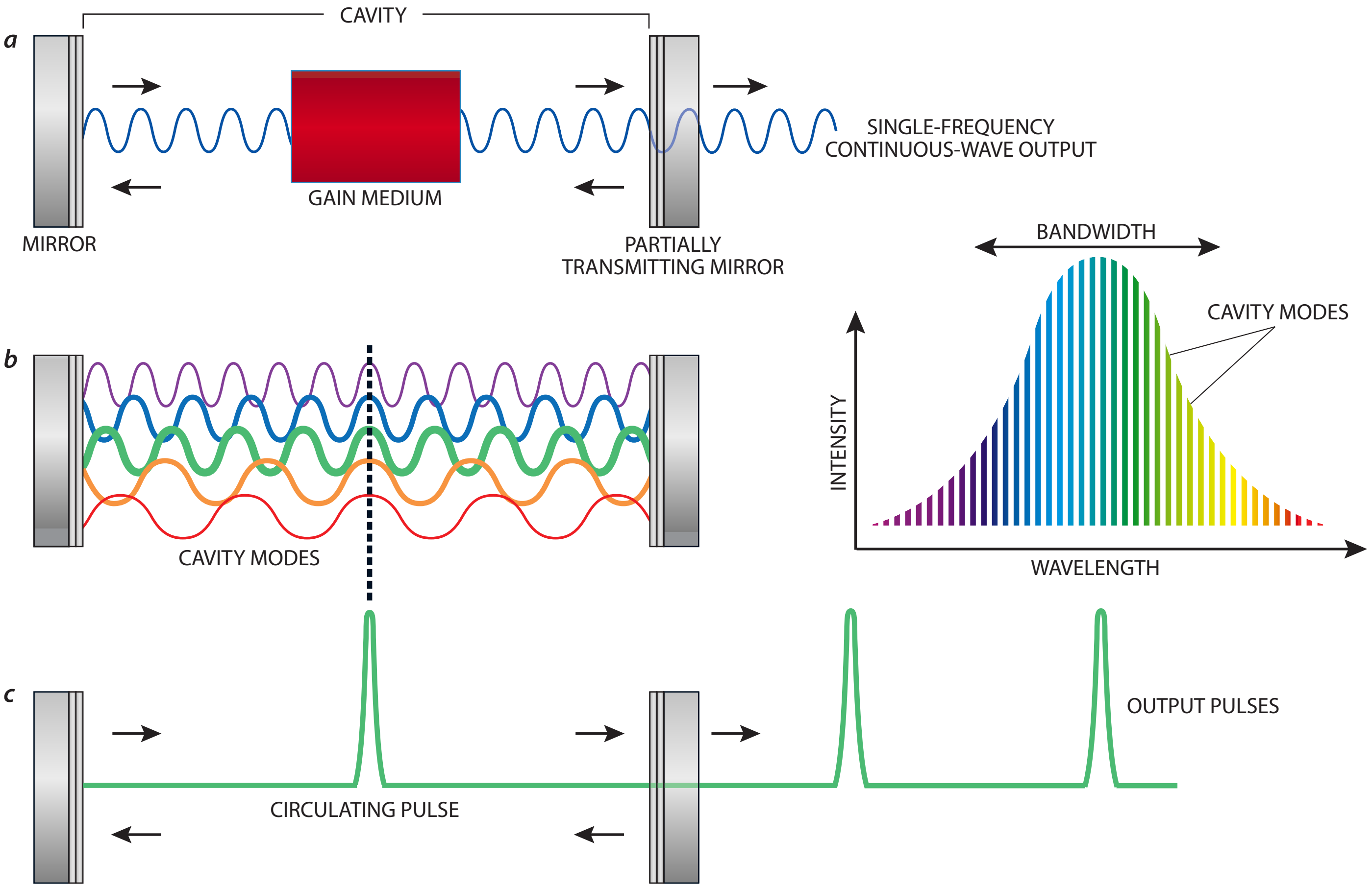
Such applications were out of the question only a decade ago, when femtosecond-pulse lasers were bulky, inefficient and unreliable. Today revolutionary advances have led to dependable, compact femtosecond lasers that can be integrated as an internal component in portable imaging or diagnostic equipment. This revolution in the design of femtosecond-pulse lasers is a story in itself.

The keys to any laser operation are optical amplification and feedback. In the late 1960s rock musician Jimi Hendrix amazed audiences by placing his Stratocaster guitar in front of an amplifier to invoke a wail of sustained acoustic feedback. Earlier in the same decade Theodore H. Maiman of Hughes Research Laboratories in Malibu, Calif., had done something similar with light: he demonstrated that an excited ruby rod placed in a cavity to provide optical feedback could produce an intense beam of laser light. The cavity is nothing more than the space between a pair of mirrors; the rod acts as the gain medium, or optical amplifier [*see illustration on next page*]. Light bounces back and forth in the cavity, building in intensity. Usually one of the mirrors is partially transmissive, allowing a portion of the light to escape and form the familiar laser beam. The cavity can support only light of certain wavelengths, or modes, that fit a whole number of times between the mirrors. Modes are the optical equivalent of the harmonic notes on each string of Hendrix's guitar.



LASER-INDUCED FLUORESCENCE for imaging conventionally produces light along all of the beam (*a*). Ultrashort pulses of longer wavelength can improve the image quality by producing fluorescence mainly at the focus of the laser (*b*).

LAURIE GRACE



FEEDBACK AND AMPLIFICATION drive the "lasing" process. Light reflecting back and forth between two mirrors (*a*) is amplified each time it passes through an excited gain medium. A continuous beam emerges through a partially transmitting mirror at one end. When many different wavelengths, or modes, of light oscillate in the cavity in precise synchrony (*b*), they add up to produce an intense pulse (*c*). A periodic sequence of pulses emerges through the partially transmitting mirror.

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A well-controlled continuous-wave laser emits a constant beam of light of a color that corresponds to the frequency of one of these modes. A short laser pulse, however, must contain a large range of frequencies, like a chord made up of many notes. (This requirement is related to Heisenberg's uncertainty principle; shorter pulses must have broader bandwidth, just as a particle confined to a precise location must have a wide spread of possible velocities.) A 10-femtosecond light pulse, for example, has an associated spectrum spanning roughly 100 nanometers. This is a huge range—in visual terms, it would span one third of the wavelengths of light we can see, all the colors from cyan to orange. The red beam of a typical continuous-wave diode laser, in contrast, has a bandwidth of less than a nanometer.

To generate an ultrashort pulse, these many thousands of modes must be locked together in phase. Imagine a row of bells, each of different tone, swinging in a bell tower. When the bells swing randomly, the result is a steady cacophony. In contrast, when swinging in synchrony at regular intervals, they produce a sequence of loud, equally spaced chords. Similarly, in so-called mode-locked operation, all the light within a laser's optical cavity is confined to a discrete ultrashort pulse that circulates between the mirrors [*see illustration above*]. The laser emits a periodic sequence of light pulses through its partially transmissive mirror.

Broadband Gain Crystals

Amplifying a wide range of frequencies requires special broadband gain media. The earliest generation of tunable ultrashort-pulse lasers (ones in which the output frequencies can be varied) used jets of colorful organic dyes dissolved in viscous solvents. These dye lasers tended to be large, complicated and high-maintenance. They typically produced an average output of only a few milliwatts, despite needing high electrical powers to be run. For producing the shortest pulses (20 to 30 femtoseconds), the performance of dye lasers proved too limited and unreliable for many applications. Also, the dye-solvent combinations were not without their hazards, especially when circulated at high pressure through small nozzles. (The dyes are optically exhausted by each pulse and so must be rapidly refreshed.) Some laser scientists still talk wistfully of their quite literal baptism into the field of ultrashort-pulse research and like to show off the range of dye stains on their lab floor and ceiling!

The first major step toward more user-friendly femtosecond lasers was the discovery of modern broadband crystals that can emit and amplify wavelengths ranging from the visible to the mid-infrared (about 3,000 nanometers). The most popular such material, titanium-doped sapphire, or Ti:sapphire, was developed by Peter Moulton of M.I.T.'s Lincoln Laboratory. Ti:sapphire can amplify wavelengths from about 700 to 1,100 nanometers and can support pulses shorter than four femtoseconds.

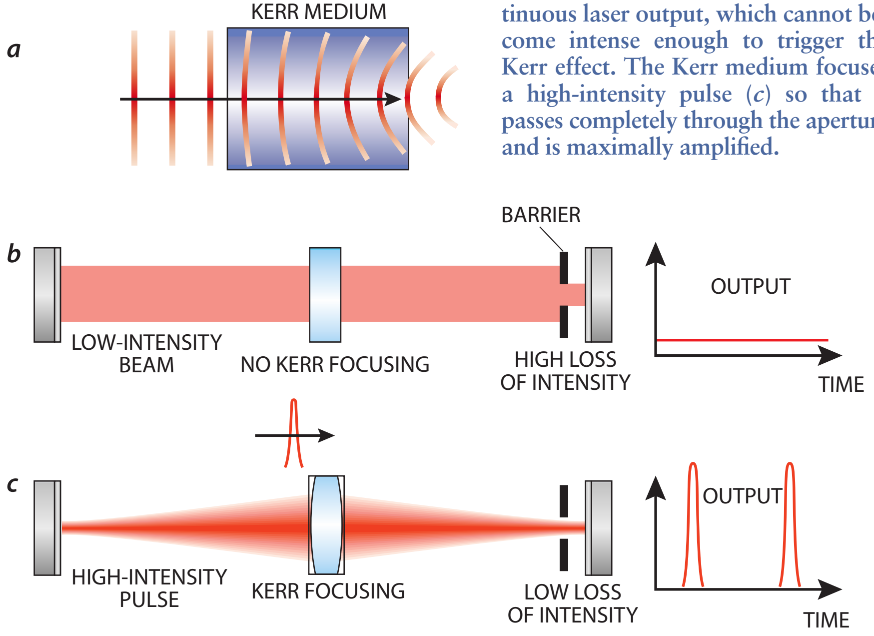
A major challenge with these new broadband materials was encouraging the laser to produce a periodic sequence of pulses, instead of continuous-wave light, by successfully locking the many millions of modes in phase. One of the early techniques for generating ultrashort laser pulses from Ti:sapphire used two optical cavities that were coupled together and precisely matched in length. But while optimizing such a mode-locked laser in 1989, researchers at the University of St. Andrews in Scotland were astonished to see pulses being produced with only one cavity.

Those researchers and several other groups concluded that this self-mode-locking relies on the optical Kerr effect occurring inside the Ti:sapphire crystal. This phenomenon arises because in a transparent material such as glass or Ti:sapphire, light of sufficiently high intensity travels slower than low-intensity light. A laser beam is most intense at its center, so light at the edges of the beam travels faster. The result is equivalent to passing the beam through a convex lens and is called self-focusing, or Kerr lensing, of the laser beam [*see illustration below*]. This effect can self-mode-lock, or Kerr lens mode-lock, a laser by degrading the amplification of a continuous beam relative to that of a circulating light pulse. The weakened continuous beam is spread over the entire cavity length, and its intensity remains too low to trigger Kerr focusing. A pulse evolves when a momentary large fluctuation of light intensity, part of the optical noise in the cavity, is Kerr focused and therefore highly amplified. The resulting pulse appropriates essentially all the available amplifier energy. In essence, the laser "prefers" to concentrate its energy into such a pulse and promptly locks the modes in phase to achieve it. For the first demonstrations of Kerr lens mode-locking at St. Andrews, the researchers started the pulse evolution process by tapping on one of the cavity mirrors to induce an initial burst of (optical) noise.

The Kerr effect also extends the bandwidth of an evolving pulse, which can be further exploited [*see illustration on page 79*]. Kerr lens mode-locking produced, for the first time, ultrashort pulses that could be tuned over a broad frequency range, at unprecedented power levels [*see top illustration on next page*]. The technique has proved to be the simplest, most elegant way to produce femtosecond pulses yet reported. Modern ultrashort-pulse lasers incorporate several refinements but retain the basic simplicity of the mode-locking process.

New Mirrors and Pumps

One significant innovation has been an ingenious type of absorbing mirror made from semiconductors. An absorbing component of these mirrors spoils their reflectivity for low levels of light, but at sufficiently high intensities, the absorber becomes saturated, and the mirror's reflectivity increases. By reflecting higher intensities more efficiently, the mirrors favor pulse generation in the cavity over continuous-wave output, much as with Kerr lens mode-locking. The devices have the added advantage that they can initiate the evolution of a pulse from very low levels of background noise within the cavity. In 1991 researchers at AT&T Bell Laboratories first demonstrated such lasers.



OPTICAL KERR EFFECT causes light of sufficiently high intensity to travel slower than low-intensity light. A Kerr medium thus acts like a focusing lens on a beam that has very high intensity at its center (*a*). A barrier with a small hole (*b*) suppresses continuous laser output, which cannot become intense enough to trigger the Kerr effect. The Kerr medium focuses a high-intensity pulse (*c*) so that it passes completely through the aperture and is maximally amplified.

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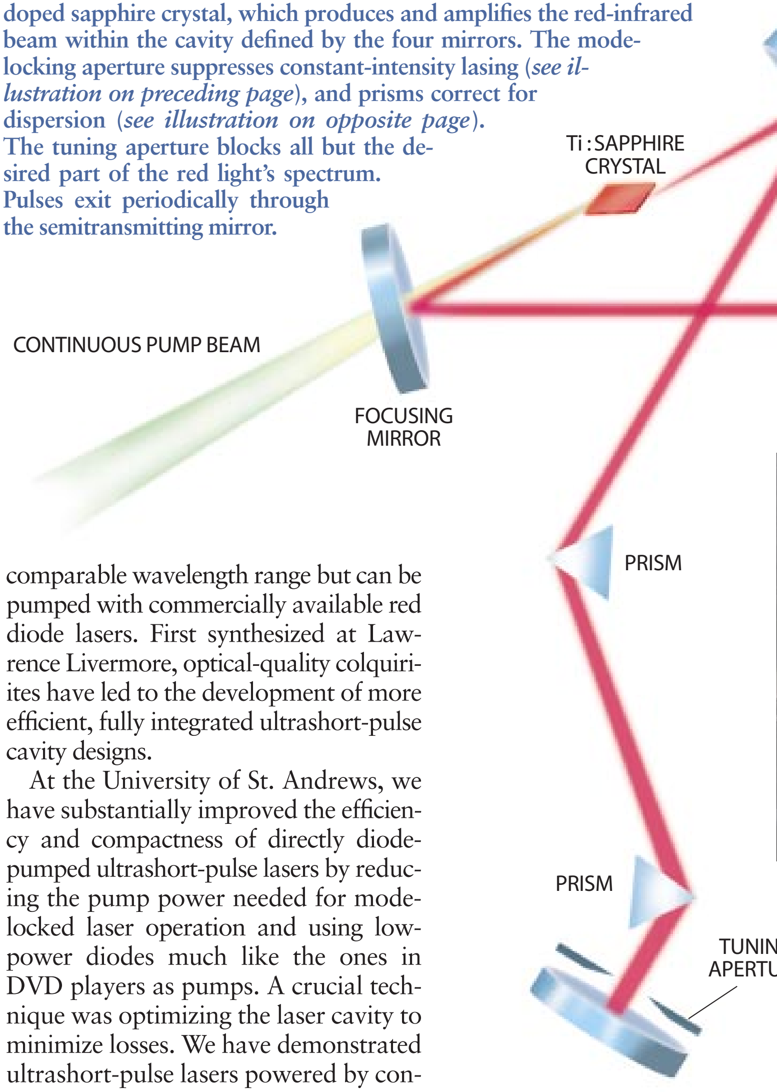
The discovery of these modern mode-locking mechanisms made ultrashort-pulse lasers much easier to operate and brought immediate commercial success to femtosecond Ti:sapphire lasers. A number of key improvements still had to be made, however—most notably in the excitation sources, or pumps, for these laser systems. Just as a guitar amplifier needs electrical power, so a laser needs power to amplify the light of its beam. In the case of Ti:sapphire crystals, a continuous-wave pump laser provides this drive power: the pump beam shines into the crystal, exciting atoms that subsequently relax by contributing more light to the pulsed laser beam. Early Ti:sapphire lasers were pumped by argon-ion lasers—big devices that consume tens of kilowatts of electrical power to produce 10 to 20 watts of blue-green light. The expense of operating and maintaining such lasers added to their unattractiveness.

Nowadays we can pump Ti:sapphire and kindred materials with efficient solid-state lasers (which are in turn pumped by compact, high-power diode lasers). These diode-pumped solid-state lasers outclass their argon-ion predecessors in almost every respect: supplying up to 10 watts of green light in a higher-quality beam, occupying less than one tenth of the space, operating off a standard power plug and costing much less to run.

The next step is obvious: remove the intermediate solid-state laser and directly pump an ultrashort-pulse laser with a diode laser. This reduction from three stages to two will reduce device size and further enhance efficiency. Unfortunately, direct pumping of Ti:sapphire is not likely in the near future, because diode lasers with the required wavelengths and output power have not yet been developed. But diodes have pumped a number of other laser crystals, producing output pulses that compare favorably with some Ti:sapphire lasers. A lower-power example is the colquiriites, named after the Colquiri tin mine in Bolivia where they were discovered. Chromium-doped colquiriites make an excellent alternative to Ti:sapphire, because they oscillate over a

KERR LENS MODE-LOCKED LASER similar to the first one developed produces high-power ultrashort pulses. A green laser beam excites the titanium-doped sapphire crystal, which produces and amplifies the red-infrared beam within the cavity defined by the four mirrors. The mode-locking aperture suppresses constant-intensity lasing (*see illustration on preceding page*), and prisms correct for dispersion (*see illustration on opposite page*). The tuning aperture blocks all but the desired part of the red light's spectrum. Pulses exit periodically through the semitransmitting mirror.



COMPACT DESIGNS of ultrashort-pulse lasers have revolutionized their potential for real-world applications. The design pictured here is powered by AA batteries and delivers half-kilowatt pulses of light. (A golf ball is shown for scale.)

LAURIE GRACE (*illustration*); JOHN-MARK HOPKINS *University of St. Andrews (photograph)*

comparable wavelength range but can be pumped with commercially available red diode lasers. First synthesized at Lawrence Livermore, optical-quality colquiriites have led to the development of more efficient, fully integrated ultrashort-pulse cavity designs.

At the University of St. Andrews, we have substantially improved the efficiency and compactness of directly diode-pumped ultrashort-pulse lasers by reducing the pump power needed for mode-locked laser operation and using low-power diodes much like the ones in DVD players as pumps. A crucial technique was optimizing the laser cavity to minimize losses. We have demonstrated ultrashort-pulse lasers powered by conventional AA-size batteries in which the laser occupied an area smaller than a page of this article [*see photograph at right*]. A laser of this design produces 100-femtosecond pulses at average powers of around 10 milliwatts. The total power consumption, one watt, is a substantial improvement on the 100 kilowatts used by mode-locked dye lasers that had similar output powers.

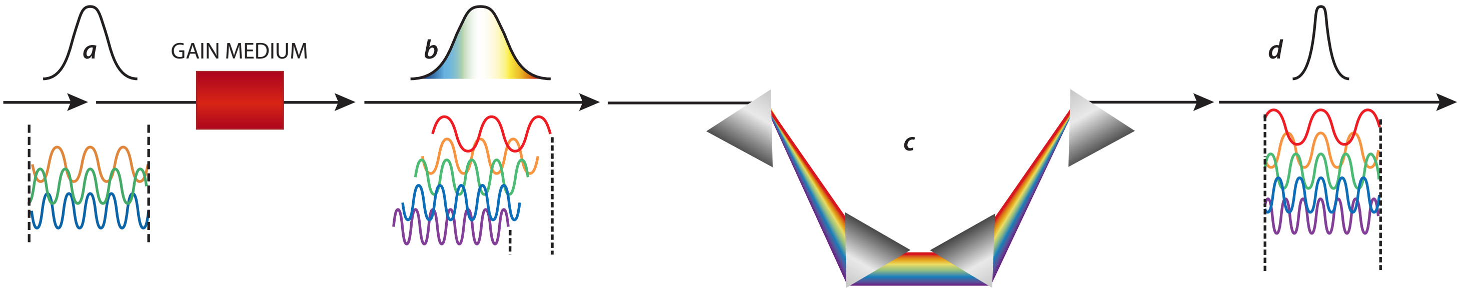
Small fiber lasers can also generate femtosecond pulses if tunability is not required. Fiber lasers use short lengths of doped optical fiber as the gain media. This type of laser provides compact, efficient sources of femtosecond pulses and is ideal for emerging industrial applications. Earlier this year researchers at IMRA America in Ann Arbor, Mich., reported average output powers greater than 10 watts from a femtosecond-pulse fiber laser.

The ultimate in compactness will come when femtosecond pulses are available directly from special laser diodes. For now, however, the current generation of all-solid-state ultrashort-pulse lasers has permitted these lasers to graduate from specialist laboratories to real-world applications of the type discussed earlier.

Highest Powers

At higher energies the peak intensity of an ultrashort pulse can damage conventional laser optics, changing the properties of the medium and even breaking it down. (In fact, a proposed application of high-power ultrashort pulses is to discharge thunderclouds by ionizing a conducting path in the air.) For a long time, these problems limited focused laser intensities to about 10^{15} watts per square centimeter. In 1985 Gérard A. Mourou and Donna Strickland, then at the University of Rochester, developed a technique, known as chirped-pulse amplification, that overcomes these difficulties. The pulses are stretched out by a process known as chirping, which lowers their intensity and lets them be amplified by a conventional gain medium. The amplified stretched pulses are then recompressed using sturdy diffraction gratings in a vacuum.

Early designs required many stages of amplification and were confined to large laboratory installations. Today we have benchtop terawatt (10^{12} watts) lasers with output beams that can be focused to extremely high intensities (10^{18} watts per square centimeter). They have been used to create plasmas that in turn produce ultrashort pulses of coherent soft x-rays, which are useful for microscopy and lithography. In the very high electric fields in these plasmas, electrons can start behaving relativistically, opening up new avenues of research in special relativity and quantum mechanics. Nuclear fusion of deuterium has recently been demonstrated at the focus of a tabletop system that pro-



INTENSE PULSES EVOLVE under the influence of several effects during each passage through a laser cavity. When an intense pulse (*a*) passes through a gain medium, the Kerr effect generates waves of shorter and longer wavelengths, and dispersion separates the component waves, lengthening the pulse (*b*). A system of prisms (*c*) can undo the dispersion to produce an optimally short pulse after many round-trips (*d*).

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vides 35-femtosecond terawatt pulses.

Large laser facilities have achieved on-target intensities as high as 2×10^{21} watts per square centimeter and peak pulse powers of petawatts (10^{15} watts), 1,000 times greater than the power that is dissipated in a lightning strike. By radiation pressure and other effects, such lasers can accelerate matter at rates of 10^{22} times the earth's gravity—an acceleration much greater than that near a solar-mass black hole! They can provide temperatures and pressures comparable to those inside stars, permitting studies of stellar dynamics. Working with focused intensities of 10^{30} watts per square centimeter, physicists will be able to create matter-antimatter pairs of particles. Such feats will further investigations of quantum electrodynamics, which describes the quantum behavior of charged particles and electromagnetism in the most exacting and intricate detail.

The other frontier is that of shortest pulses. Researchers have used the huge bandwidth of pulses shorter than 10 femtoseconds for precise measurements of optical frequencies. The modes of a mode-locked laser are uniformly spaced in frequency like the teeth of a comb [*see illustration on page 76*]. Such a "comb" can be used as a standard for measuring frequencies that are hard to evaluate directly. Researchers have used this technique to measure optical atomic energy transitions with precision 1,000 times greater than ever before. This result provides a new and independent way to determine the fine structure constant, which dictates the strength of the electromagnetic force.

The record for well-characterized short pulses stands at 4.5 femtoseconds, produced from Ti:sapphire lasers. Until now, ultrashort pulses have been understood using a theory in which the envelope of the pulse varies slowly compared with the optical oscillations of the light. Pulses shorter than five femtoseconds have only a few optical cycles in their envelope and push the theory to its limit. Soon we will enter a new regime of physics: pulses with durations comparable to a single optical cycle.

The Future

Ultrashort-pulse lasers spanning a range of powers—more than 17 orders of magnitude—are driving forward many areas of scientific research and industrial applications. From the deep imaging of living tissue to answering fundamental questions about the universe, the shortest man-made events are proving their worth. Just as femtosecond pulses have provided the ability to observe molecular processes and motions of atoms, so attosecond (one thousandth of a femtosecond) pulses will provide new insights as the motions of electrons, protons and neutrons become directly observable.

The field of ultrafast science and technology will progressively influence all our lives, particularly as biological imaging and laser-based medical procedures continue to develop. The lasers should also produce major new pharmaceutical discoveries, such as how certain drugs function at the chemical level. Other upcoming roles include the coherent control of electric currents in semiconductor devices and in femtosecond networks for digital optical communications.

When the laser was invented, some called it a solution in search of a problem. Today lasers are ubiquitous in consumer technology, from CD players to supermarket checkout scanners. Since their emergence in the mid-1960s, ultrashort-pulse lasers have embarked on a similar journey from the esoteric to the truly practical. Already they provide the preferred solution to an impressive variety of real-world tasks, and in the future they will enhance quality of life and contribute wealth to the world economy.

The Authors

JOHN-MARK HOPKINS and WILSON SIBBETT work in the School of Physics and Astronomy at the University of St. Andrews in Scotland. Hopkins won a thesis prize for his work on compact, low-threshold femtosecond lasers in the ultrashort-pulse laser research group that is headed by Sibbett. He received his Ph.D. in 1999 and is now a research assistant in the semiconductor physics group. Sibbett received his Ph.D. from Queen's University in Belfast in 1974 and has been Professor of Natural Philosophy at St. Andrews since 1985. In addition to his groundbreaking laser research, he is active in science policy as a member of the U.K. Engineering and Physical Sciences Research Council. St. Andrews, Scotland's oldest university, was founded 1.86×10^{25} femtoseconds ago, in the year 1410.

Further Information

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