How Short Is Ultrashort?

Our inability to accurately measure ultrashort pulses has held back applications in this field. But all that is changing.

By Howard Rausch

It's a humbling experience to investigate ultrashort pulses, even if your only objective is journalistic. At first it was discouraging to realize that I could not truly conceive of "ultrashort". I have no problem with *short* in various degrees. But *ultrashort*, I learned, is another world.

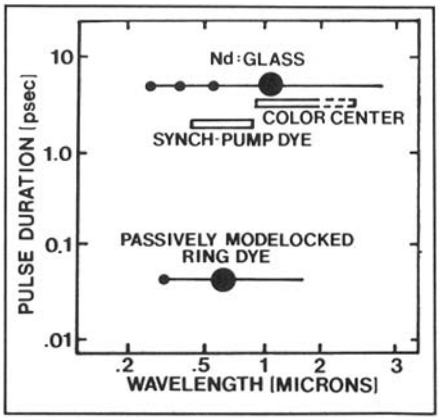
I was cheered up a bit to learn that hardly anybody else fully appreciates ultrashort either. Not the people who deal daily with events measured in femtoseconds (10^{-15} second). Nor even those who work in the slower, instant-replay-speed world of the picosecond (10^{-12} second). Even a picosecond, I came to realize, is shorter than the interval from the moment the traffic light turns green until the driver behind you honks his horn.

Just how short is a femtosecond? Well, there are as many of them in one second, it turns out, as there are seconds in five million years. Five million years ago, remember, our ancestors were just coming down out of trees.

If you prefer physical comparisons, consider this: In a single femtosecond, light travels only one hundred-thousandth of an inch. In the same interval, if our watches are synchronized correctly, an electron carrier travels less than one thousandth of a micrometer in a semiconductor.

Intriguing applications

In addition to their brief duration, ultrashort pulses have two properties that enhance their value in research: coherence and high peak power. Together, these properties suggest intriguing applications.



Ultrashort-pulse lasers, with wavelength coverage and typical pulse durations. Dots indicate primary oscillating wavelengths and easily generated harmonics. Connecting lines indicate that all intermediate wavelengths have been generated. White bars indicate continuously tunable, continuous-wave pulse trains, although a variety of pumping sources or gain media are required. Chart by Erich P. Ippen at MIT.

The search for ever-faster computers, for example, is spurring the development of smaller and faster semiconductor devices — and of test instruments of comparably short response times.

Semiconductor circuits are already so fast that many of their internal processes cannot be measured electronically. These processes can be studied only by optical pulse techniques, which are 1,000 times as rapid as their electronic counterparts.

Ultrafast optical diagnostics are increasing our understanding of rapid energy and momentum relaxation processes and of high-speed transport effects in semiconductor microstructures. Time-resolved absorption measurements provide a unique means of observing the influence of "hot" electrons in optically excited semiconductors. For example, C. V. Shank and colleagues at AT&T Bell Laboratories have traced changes in temperature of the electron-hole plasma as a function of time.

In addition to opening new areas for scientific investigation, the improved understanding of ultrafast phenomena has led to the development of new devices. The generation of picosecond electrical pulses, first reported by David H. Auston of AT&T Bell Laboratories in 1975, provides a way to combine optics and electronics for obtaining new information about very high-speed microelectronic devices. High-speed photoconductive switches, samplers, and mixers have been fabricated. Photoconductive detectors have produced responses as fast as 70 picoseconds to wavelengths as long as 1.6 micrometers; at shorter wavelengths, responses have been recorded as fast as four picoseconds.

Optical communication

Across the ever-narrowing line between computing and communication, compact sources of ultrashort pulses hold enormous promise for optical communications and for ultrafast signal processing.

At AT&T Bell Laboratories in Holmdel, New Jersey, Linn F. Mollenauer and colleagues have achieved a "self maintaining" property in optical fiber transmission. They have also propagated, split, and compressed "optical solitons"—pulses that either do not change shape or have shapes that vary periodically with propagation along the fiber. This is accomplished by using index-of-refraction linearity to compensate for the pulse-broadening effect of dispersion. Fortunately, this compensation occurs around 1.55 micrometers, a particularly efficient regime for communication along optical fibers.

"Communication links based on soliton propagation would be eminently practical," Mollenauer and Roger Stolen wrote in *Laser Focus*. "In fact, it is possible that soliton propagation will some day make systems based on tuning to the wavelengths of zero dispersion obsolete." When that happens, data transmission rates of tens of gigabits per second could be considered.

Studying molecular dynamics

In addition to their value in semiconductor studies, temporal measurements are important for improving understanding of relaxation processes in molecules, fluctuations in liquids, and the dynamics of highly excited plasmas. In all of these fundamental material processes, the ultrafast phenomena are difficult to study by measuring spectral widths and shapes alone.

Coherence of ultrafast pulses adds the ability to investigate transient coherent phenomena and to separate dephasing from energy relaxation. Another important property—high power—amplifies many nonlinear optical effects, allowing the study of dynamic processes after excitation and facilitating various nonlinear spectroscopic techniques.

A natural application of picosecond, and shorter, pulses is the study of relaxation in organic molecules. Increased resolution can extend observations from qualitative to quantitative nature.

Ultrashort pulses also have contributed to the study of photosynthesis. The ability to vary excitation wavelength, and the possibility of exciting specific groups of pigment molecules, have facilitated measurement of photophysical events that occur in picosecond time frames in these and other photochemically sensitive systems.

Fluorescence decays in the light-harvesting system of barley chloroplasts have been measured with picosecond excitation and single-photon counting. Graham Fleming and colleagues at the University of Chicago, who have pioneered such investigations, expect time-resolved fluorescence techniques to provide important information about the mechanisms of energy transfer and the organization of the light-harvesting system in plants.

Produced by modelocking

Short laser pulses are generated by a process called modelocking. Laser modes at different frequencies are locked together in phase to produce a coherent oscillation over a band broad enough to produce a short optical pulse. This is accomplished in two ways: actively and passively.

In active modelocking, loss or phase

modulation is introduced into the laser resonator. Passive modelocking, which generally produces shorter pulses, involves the use of a saturable absorber in the cavity, passing intense pulses with less loss than occurs when the light level is constant but low. Under proper conditions, the laser output breaks up spontaneously into a train of modelocked pulses. By adding pulse compression, it is possible to produce optical flashes as short as a few tens of femtoseconds.

But how do you measure ultrashort optical pulses that are 1,000 times as fast as can be handled by conventional electronics? Most present methods rely on the use of nonlinear optical interactions. In a nonlinear material, one picosecond pulse can be used to probe either itself or another pulse. The method was developed in 1977 by Shank working with Erich P. Ippen at AT&T Bell Laboratories; Ippen is now at the Massachusetts Institute of Technology.

In a variation, one ultrashort pulse is used to probe the state of the medium following excitation by a pump pulse. A third method, involving a picosecond streak camera, is particularly useful in studies of time-resolved luminescence.

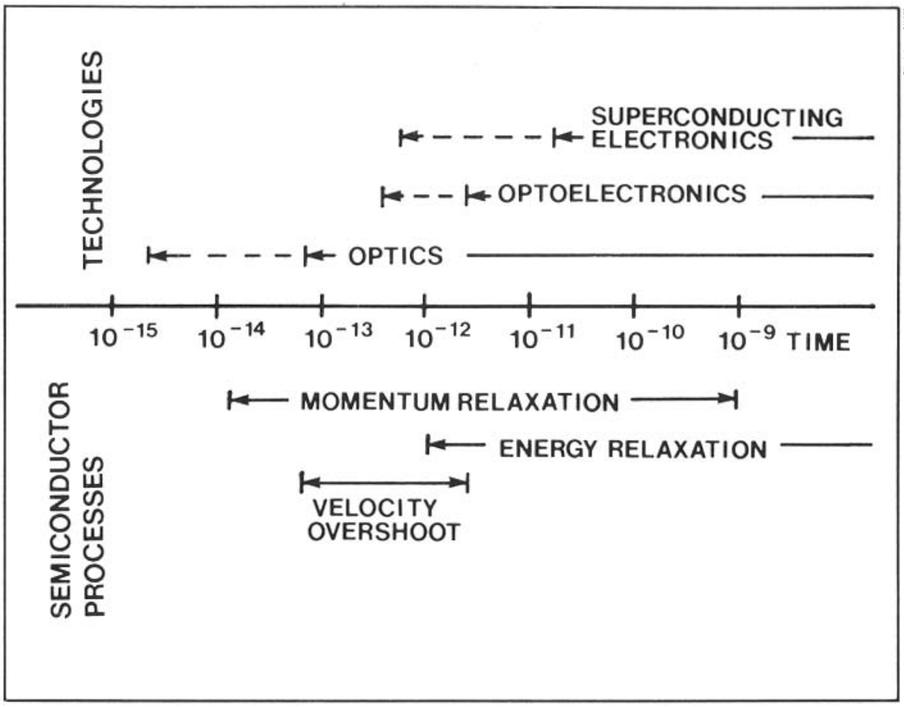
Speeding electronic measurements

If electronics is too slow to measure optical pulses, shouldn't the reverse work? Can optical pulses be used to make electronic measurements with enhanced speed? The answer is "yes, if"—if you have a transducer fast enough to couple the two technologies. David H. Auston and colleagues showed in 1980 that photoconductors, made of semiconductors with high-defect densities, can act as optical-electronic transducers with response times shorter than eight picoseconds. When illuminated by picosecond optical pulses, such photoconductors function as electrical pulse generators and sampling gates. They have been used to measure the electronic response of a field effect transistor in gallium arsenide, for example.

With further improvements in the photoconducting materials and circuits, Auston has predicted development of an electronic measurement system with resolution within one picosecond.

Equally exciting is the prospect of a family of ultrahigh-speed interfaces between optics and semiconducting electronic devices. Shank and Auston have speculated that single-mode optical fiber waveguides might some day transmit data at rates as high as one terabit—10^{12} bits—per second over kilometers. Fiber is a leading candidate for high-speed data links between electronic processors because optical interconnection of small electronic circuits could avoid the inefficiency of converting electrical to optical signals.

In the beginning, applications were held back by the need to develop accurate ways to measure record short pulses and their effects. But progress has been rapid. Last year, the *Journal of Quantum Electronics* devoted a special issue to ultrashort pulses; many papers discussed applications. And on June 12-15, 1984, the Optical Society of America will hold a topical meeting on the subject in Monterey, California.



Time line compares fast physical processes in semiconductors with technologies required for controlling and measuring them. From C. V. Shank and D. H. Auston in *Science* 215, 12.