PERSPECTIVE | LASER PHYSICS

Toward Attosecond Pulses

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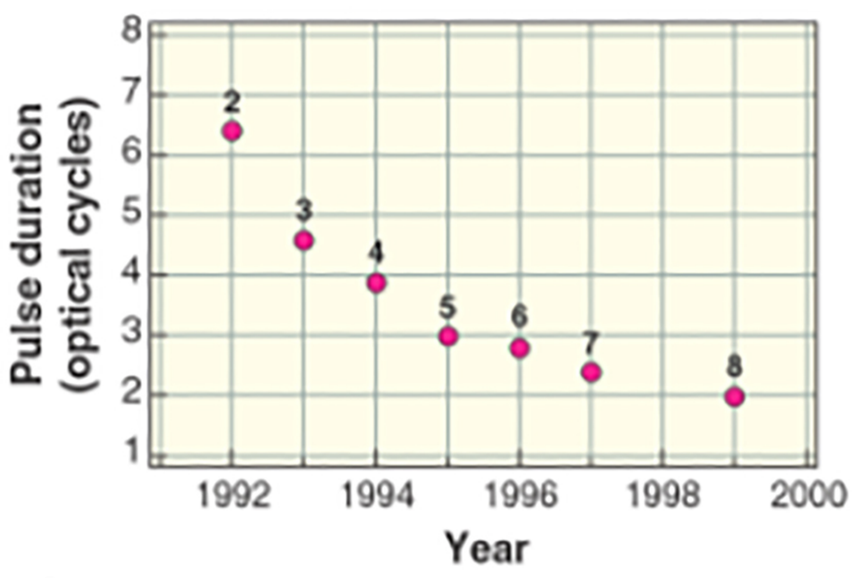
In which scientific discipline would you expect to find the fastest recorded events? Surprisingly, the answer is not electronics, or even atomic physics, but optics. In the last decade, laser science has succeeded in generating pulses of light lasting less than 10 femtoseconds (fs), where 1 fs = 10^{-15} seconds. Femtosecond pulsed lasers have provided unprecedented insights into molecular processes such as reaction dynamics. So far, most research has concentrated on pulses in the visible or near-infrared part of the light spectrum. At these wavelengths, the optical wave takes about 3 fs to complete one oscillation, so that state-of-the-art 5-fs laser pulses correspond to less than two optical cycles. Optical pulses much shorter than this require substantial effort to produce, and, because light propagates as an oscillating electromagnetic wave, they are fundamentally limited to the "single-cycle" duration of about 3 fs.

Now, a new area of experimental physics is emerging, one sufficiently radical to be defined by its own prefix—attosecond science. By using femtosecond optical pulses to generate wavepackets in the soft x-ray region, where wave cycles last for only about 50 attoseconds (as) or 50 × 10^{-18} seconds, it should be possible to produce multicycle x-ray pulses with subfemtosecond durations. In this issue, Drescher *et al.* (1) report a first step in this direction. The authors have both created and measured x-ray pulses with durations below the carrier wave period of the original optical pulse.

Molecules are characterized by bending and stretching motions with time periods lasting several tens of femtoseconds or more, and femtosecond pulses can be used to study these vibrational motions. Measurements are made using the "pump-probe" technique, in which a strong "pump" pulse excites a collection of molecules into an initial energetic state, followed by a weaker time-delayed "probe" pulse that samples changes in the molecular behavior such as optical absorption. By recording many samples at different pump-probe time delays, one can construct a time-domain picture of the molecular response to excitation, which provides insights into its chemistry. The resolution of this technique depends directly on the pump and probe pulse durations, and therefore the extremely short pulses demonstrated by Drescher *et al.* offer substantially improved accuracy in these measurements. Furthermore, it might be possible to extend such studies to the analysis of atomic dynamics, which occur on much faster time scales than molecular vibrations. In their paper, Drescher *et al.* suggest that

ultrashort x-ray pulses might be used to study the rapid motions of inner-shell electrons, which are tightly bound to the nucleus, or could provide information about fast ionization processes.

The route to attosecond science has been paved over the last decade by huge advances in the generation and manipulation of ultrashort laser pulses (**2**–**8**). Durations of optical pulses are now approaching a fundamental plateau at two optical cycles (see the figure), or about 5 fs for electromagnetic waves in the visible and near infrared. To achieve substantially shorter pulses therefore requires working at shorter wavelengths. Fortunately, it is possible to generate laserlike beams of x-ray pulses by focusing high-intensity ultrashort laser pulses onto a suitable target, such as the neon gas cell used by Drescher *et al.* The mechanism by which short optical pulses can generate even shorter x-ray pulses relies on the principle of harmonic generation. Any mechanical system that experiences a restoring force dependent on its displacement from some equilibrium position can oscillate at a well-defined resonant frequency. An isolated atom is one example of such a system, in which the outer electrons experience a restoring force due to the nuclear Coulomb field. These electrons are easily perturbed from their equilibrium position by a strong optical field, and the combination of restoring and applied forces results in complex motion involving frequencies much higher than that of the incident wave. As they respond to these forces, the electrons dissipate energy as high-frequency electromagnetic radiation, and wavelengths in the x-ray region are generated at harmonics of the original optical frequency.



Reaching a plateau.

The steady decrease in the duration of optical pulses produced by femtosecond lasers over recent years has begun to slow down, implying that new approaches will be needed to produce subfemtosecond wave packets. The "single-cycle" limit for typical optical pulses has a duration of 2.5 to 3 fs and corresponds to the time taken for the propagating optical wave to complete one full oscillation. Numbers in the figure correspond to reference numbers.

In their experiment, Drescher *et al.* isolated the highest frequency harmonics and, using a novel method, measured the duration of these x-ray pulses. The method uses a portion of the original laser pulse that created the x-ray pulse like a fast shutter to gate the intensity of different parts of the x-ray pulse profile. The authors demonstrate pulse durations of around 2.5 fs—certainly the fastest events ever recorded and slightly shorter than the optical period of the generating optical wave. Truly attosecond-domain pulses still remain just out of reach, but the generation and measurement tools demonstrated here bring them another step closer.

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