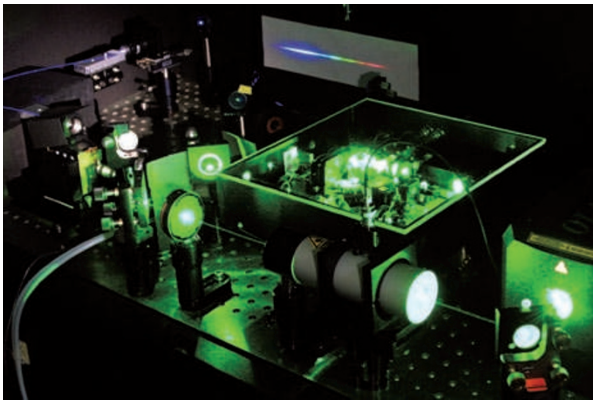
MILESTONE 16

Absolutely accurate

The ability to measure optical frequencies with high precision and stability has led to a plethora of applications, including optical atomic clocks, optical metrology, high-resolution spectroscopy, and even the global positioning systems used in mobile telephones and navigation systems for cars.

Traditionally, precision measurements have been made by comparing the beat frequency between two optical frequencies with a microwave reference, which is a standard based on a specific transition between hyperfine levels of the caesium-133 atom. However, the situation changed when light pulses became available with durations on the scale of femtoseconds. Early approaches to generating such 'ultrashort' pulses were plagued by intrinsic instabilities and uncertainty about the underlying mechanisms. A remedy came, in 1981, when Charles Shank and co-workers at Bell Laboratories invented the colliding-pulse mode-locked (CPM) laser, which generated the first coherent photon wave packets in the sub-100-fs regime.



Courtesy of Ted Hänsch and Max-Planck Institut für Quantenoptik

Crucially, the introduction of titanium-doped sapphire (Ti:sapphire) as a broadband gain medium in the near-infrared spectral region revolutionized the generation and amplification of ultrashort pulses. The first broad-bandwidth solid-state laser was demonstrated by Peter Moulton in 1986, and, together with the subsequent demonstration of self-mode locking in Ti:sapphire lasers by Wilson Sibbett and co-workers in 1991, this paved the way to femtosecond pulses with high peak powers and good tunability. Sibbett's group produced pulses with durations as short as 2.0 ps and, using an intracavity dispersion compensation in a mode-locked Ti:sapphire laser, they managed to achieve pulse durations as short as 60 fs and peak powers of 90 kW. In 1985, Gérard Mourou and co-workers introduced a chirped-pulse amplification scheme that allowed them to push the intensities of femtosecond lasers to $>10^{21}$ W cm^{-2}. In the 1990s, dispersion control was dramatically simplified through the use of chirped multilayer mirrors, which extended the oscillators' performance into the few-cycle frontier.

The development of reliable high-intensity, sub-100-fs laser technology based on these breakthroughs has stimulated an explosion of activity, leading to fundamental studies into the ways photons and matter interact on very short timescales. Femtosecond lasers have been used as accurate 'stopwatches' to observe in real time the energy transfer and storage process, which is at the heart of many chemical processes, resulting in the 1999 Nobel Prize for Chemistry being awarded to Ahmed Zewail. More recently, the broadband coherence of femtosecond pulses has been harnessed in the invention of the femtosecond frequency comb, which is an optical measurement technique that can precisely measure different colours or frequencies of light. John Hall and Theodor Hänsch shared half of the award for the 2005 Nobel Prize in Physics "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique".

Their ease of fabrication and simplicity, compared with techniques based on a microwave standard, have helped to establish frequency combs as excellent frequency reference sources and measurement tools. They are nowadays commercially available and widely used for metrological purposes. There should be more to come: optical atomic clocks using frequency combs are expected to have accuracies 100 times better than any other time-keeping systems, making them attractive for use in global satellite-navigation systems.

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