16-Femtosecond Pulse from Laser Is Shortest Yet

At the 13th International Conference on Quantum Electronics [held concurrently with the 1984 Conference on Lasers and Electro-Optics (CLEO '84) in Anaheim, California, 18 to 22 June] James Fujimoto, Andrew Weiner, and Erich Ippen of Massachusetts Institute of Technology (MIT) staked a claim for the shortest laser pulse yet. Scientists use such fleeting light to probe the kinetics of the fastest processes in nature.

Visible pulses from the MIT visible dye laser system were only 16 femtoseconds long, corresponding to about 8 cycles of red-orange light (625 nanometers). The previous record of 30 femtoseconds was held by Charles Shank, Richard Fork, Richard Yen, Rogers Stolen, and William Tomlinson of AT&T Bell Laboratories, reported about 2 years ago.

Mode locking and pulse compression are the two keys to making such short laser pulses (*Science*, 4 March 1983, p. 1027). The optical cavity of a laser can support laser oscillation at several frequencies (called longitudinal modes) subject to the constraint that an integral number of waves fits into the cavity. If all the modes can be made to oscillate with the same phase, the laser emits a train of very short but powerful pulses of light.

The duration of the pulse is inversely proportional to the number of modes, so the shortest pulses require a laser medium such as a dye that fluoresces over a wide range of frequencies. In 1981 at Bell Labs, Fork, Benjamin Greene, and Shank discovered a way to achieve efficiently and reliably mode locking in a so-called colliding-pulse ring laser and thereby obtained 90-femtosecond pulses. The colliding-pulse technique is straightforward enough that several laboratories have since built and now routinely use femtosecond lasers.

Further reduction in the pulse length requires the additional technique of optical fiber pulse compression. The idea is to controllably expand the spectral width of a pulse beyond even that of a dye laser. After increasing the spectral width of a pulse, one can then decrease the pulse length.

Building on earlier experiments by Daniel Grischkowsky and others at the IBM Yorktown Heights Laboratory, Shank and his colleagues achieved a threefold pulse compression from 90 to 30 femtoseconds by passing the amplified light from the femtosecond ring dye laser through an optical fiber and then through a pair of diffraction gratings. By way of a nonlinear optical effect (nonlinear self-phase modulation), the fiber stretches the spectral width of the pulse, and the grating pair temporally compresses it.

The MIT group has extended the same technique closer to its theoretical limit. Starting with pulses from a ring dye laser of 0.1 nanojoule energy and 65 femtosecond length, the researchers first amplify the pulse energy. A higher energy means a more intense beam in the fiber and hence a stronger nonlinear effect.

Five-nanojoule pulses passing through the fiber were spectrally broadened by about a factor of 4. The grating pair was able to compress the pulse width by the same factor, thereby generating 16-femtosecond laser pulses. Ippen said the group consistently obtains pulses from 15 to 18 femtoseconds in its experiments. It is not a one-time result.

Is there a limit to how much pulses can be compressed? It would not seem to make much sense to speak of pulses of less than 1 cycle duration. Hence, the frequency of the light sets the ultimate limit. As discussed by Tomlinson, Stolen, and Shank at CLEO '84, the amount of pulse compression can theoretically be increased by raising the intensity and shortening the fiber length. So far, however, attempts at MIT to reduce the pulse length further by increasing the light intensity in the fiber have not been successful.

Meanwhile, compression can be employed in another manner. Rather than using the colliding-pulse mode-locked ring dye laser as a source of femtosecond pulses, researchers can start with a wide variety of more conventional lasers having picosecond pulses and follow with an efficient compression scheme to access the femtosecond regime with light from the infrared through the visible.

At CLEO '84, for example, Grischkowsky discussed experiments by Bernhard Nikolaus and him in which two stages of optical fiber/diffraction grating-prism compression squeezed 5.9-picosecond pulses from a commercial dye laser to 90 femtoseconds, a factor of 65. Grischkowsky said compression factors of several hundred should be possible.

Precision Positronium Spectroscopy Tests QED

Advances in laser technology are hastening the day when the most accurate frequency measurements may be made in the optical rather than the radio-frequency or microwave domain. A case in point is a report at the quantum electronics conference by Steven Chu and Allen Mills, Jr., of Bell Labs and John Hall of the Joint Institute for Laboratory Astrophysics (National Bureau of Standards and University of Colorado), who presented the results of an improved version of an earlier experiment by Chu and Mills.

They were able to measure the frequency of the optical transition between positronium $1s$ ($1\ ^3S_1$) and $2s$ ($2\ ^3S_1$) states to within 12 parts per billion, one hundred times more accurately than before. Moreover, their optical data now give accurate spectroscopic information on positronium that is on a par with that from radio-frequency spectroscopy of small effects such as hyperfine splittings and the Lamb shift, which had been the champion technique.

Physicists consider positronium—which consists of an electron and its antiparticle, the positron, bound together—to be a good test-bed for quantum electrodynamics (QED), the quantum field theory of electromagnetic interactions. It is also the prototype for the quantum field theories of nuclear forces. Although its predictions agree magnificently with an amazing variety of experiments from atomic to high energy physics, researchers would like to know if QED is exactly correct or if it eventually will break down.

The theory has no analytic mathematical solution, so QED tests are a matter of comparing ever more accurate experiments with higher order correction terms in a perturbation series expansion. The frequency measured by Chu, Mills, and Hall agrees to within 1 percent with QED predictions when third-order terms in the perturbation series are included.

The first step in the experiment is to generate positronium, accomplished by letting bursts of from 50 to 100 slow-moving positrons strike a clean aluminum surface maintained in ultrahigh vacuum at a temperature of 300°C. About 20 percent of the positrons capture electrons from the aluminum and then thermally desorb from the surface as positronium.

To carry out ultrahigh-resolution spectroscopy on the dilute positronium gas, the researchers resorted to two-photon absorption. To reach the positronium 2*s* state from the 1*s* state requires ultraviolet light, if only one photon is absorbed. However, two blue light photons will also do the trick. If the photons come from two beams moving in opposite directions, the Doppler shifts in the frequency seen by each positronium "atom" will cancel. Hence, all atoms will absorb laser light but only when it is tuned to the resonance frequency.

From each initial burst of positrons, only a few two-photon absorption events will result. Since it is possible to detect a single charged particle, the investigators relied on photoionization of the excited positronium to measure the absorption. Luckily, the same laser light that excited positronium could also ionize the excited atoms. The experiment then consisted of scanning the frequency of the amplified light from a dye laser and monitoring the absorption by detecting the photoelectrons produced by photoionization. The width of the absorption line was less than 50 megahertz.

However, to determine accurately the frequency at which absorption occurred, a frequency reference was required. The reference was the frequency of a transition in deuterium that is known very accurately. Because the tuning range of the laser is small, the researchers first measured the frequency difference between transitions in positronium and tellurium vapor, which has an absorption line within 50 megahertz of that of positronium. They later measured the frequency difference between the tellurium and deuterium by an interferometric technique. The final result was 1,233,607,185 $\pm$ 15 megahertz.

According to the group, it may be possible to improve the accuracy by another one or two orders of magnitude. If it manages this, it will be up to the theorists to calculate additional terms in the perturbation series before a comparison with QED can be made.

High-Power Infrared Free Electron Lasers

Free electron lasers convert the energy of the electrons in an accelerator into a monochromatic, coherent, laser-like beam of photons. At a joint quantum electronics conference/CLEO '84 symposium, two groups working on infrared free electron lasers presented results obtained during the last several months.

One group from the Los Alamos National Laboratory reported the highest output power so far in near infrared or visible free electron lasers with a maximum instantaneous or peak power of 5 megawatts and an average power of 3 kilowatts. The average power is much lower because the intervals between laser pulses are considerably longer than the pulses themselves. The laser wavelength ranged from 9 to 11 micrometers.

The second team, a collaboration between researchers from TRW, Inc., and Stanford University, successfully demonstrated for the first time in an operating free electron laser a so-called tapered wiggler. This device is designed to enhance the efficiency of energy transfer between the electron and optical beams, a task that must be completed before power-hungry commercial or military applications of free electron lasers will be practical. The laser wavelength was 1.6 micrometers.

Despite a large body of theoretical work, relatively few free electron lasers have actually been operated. The TRW-Stanford free electron laser, which first operated last July, is only the third such device. Fourth is the Los Alamos device, which came on-line last November. Several other free electron laser experiments are under way around the world, some of which were discussed at the symposium, so the once rare bird should soon be more common.

Brian Newnam of Los Alamos discussed the free electron project there. The group built a 20-million-electron-volt electron linear accelerator that produces 30-picosecond-long bursts of electrons spaced 46 nanoseconds apart. The electron beam then passes through a 1-meter-long wiggler magnet. The wiggler consists of an array of dipole magnets of alternating orientation, which causes the electrons to have a sinusoidal motion.

The wiggling electrons emit synchrotron radiation. However, if the electron beam energy, the spacing between neighboring dipoles, and the magnetic field are properly adjusted in relation to one another, a resonance condition causes the light from each period of the wiggler to constructively interfere, thereby giving a bright light beam in a narrow band of wavelengths. Reflecting mirrors at each end of the wiggler form an optical cavity for the buildup of laser radiation. The electric field of the emitted light partitions each electron pulse into many microbunches that move in phase with the light so that energy is transferred from the electrons to the light and not vice versa. The laser wavelength is tunable by varying the beam energy or the wiggler field.

Because the electrons lose energy as light is generated, the resonance condition changes over the length of the wiggler and the transfer of energy from the electrons to the light becomes less efficient. To enhance energy transfer, accelerator experts have long advocated tapered wigglers in which the magnetic field decreases in such a way as to match the electron energy. Tapering is achieved by increasing the gap between the pole faces of the dipoles.

John Edighoffer of TRW described the TRW-Stanford experiment in which a tapered wiggler was used. The experiment was done at Stanford on the electron linear accelerator that was used in the very first free electron laser demonstration in 1976 by a Stanford group. A 66-MeV pulsed electron beam passed through a wiggler about 5 meters long. The taper could be adjusted and ranged from 0 to 2 percent.

Although the overall efficiency was not large, the experiment did verify that increasing the tapering enhanced the energy transfer. Roughly in accordance with theory for the conditions of the experiment, the efficiency rose from 0.4 percent with no taper to 1.2 percent with a 2 percent taper.

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