The impact of frequency combs

Frequency combs generated by femtosecond lasers are powerful tools for high-precision optical spectroscopy and metrology. Theodor Hänsch, who received part of the Nobel Prize for Physics in 2005 for his work in this field, spoke to *Nature Photonics* about how frequency combs have changed science.

What is a frequency comb?
A laser frequency comb is the broad spectrum produced by a mode-locked femtosecond laser and consists of several million perfectly evenly spaced spectral lines. Such laser frequency combs were conceived a decade ago as tools for the precision spectroscopy of atomic hydrogen. They have since revolutionized the way we measure the frequency of light and have become essential for many new applications that rely on the precise control of light waves.

What were the circumstances leading up to the initial study of optical frequency combs?
When I was at Stanford University more than 30 years ago, I demonstrated two-photon spectroscopy with the relatively narrow frequency comb of a synchronously pumped mode-locked dye laser. Together with Jim Eckstein and Allister Ferguson, we applied this comb as a spectral ruler to measure some of the line intervals in atomic sodium. The idea of a self-referenced octave-spanning frequency comb that could measure the absolute frequency of light came to me in 1997, after Marco Bellini and I had observed interference fringes between two laser-generated white-light continuum sources.

Did you expect the frequency comb technique to have such a significant impact?
No! I didn't expect there to be so many applications. Nonlinear frequency conversion can now produce frequency combs from the extreme ultraviolet to the terahertz region. Miniaturized comb generators have been realized by cascaded four-wave mixing in optical microresonators. The availability of commercial instruments is facilitating the evolution of new applications ranging from fundamental research to telecommunications and satellite navigation. Laser frequency combs provide the long-missing clockwork for optical atomic clocks. Laser combs are revolutionizing molecular spectroscopy by dramatically extending the resolution and recording speed of Fourier spectrometers.

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The calibration of astronomical spectrographs with laser combs will enable new searches for earth-like planets in distant solar systems and may reveal the continuing expansion of space in the universe. Laser frequency comb techniques have become essential to attosecond science, where they are used to control the electric fields of ultrashort laser pulses.

Frequency combs recently helped provide a new measurement of the size of the proton. How did this come about?
My interest has long been to develop breakthroughs in fundamental physics through the precise laser spectroscopy of simple atoms. Measuring and comparing different resonance frequencies in atomic hydrogen with the help of the frequency comb allows us to determine the charge radius of the proton, if we believe in the theory of quantum electrodynamics. However, testing this theory requires an independent measurement of the proton size. Electron-scattering experiments at big accelerators are still suffering from rather large uncertainties. However, last year, an international collaboration at the Paul Scherrer Institute in Switzerland, led by Randolf Pohl from our laboratory, looked at man-made exotic muonic hydrogen atoms. Here, the electron is replaced by a negatively charged muon, which is 200 times heavier than the electron and orbits 200 times closer to the nucleus, meaning its energy levels are much more sensitive to the proton size. From laser measurements of the $2s$–$2p$ Lamb shift, we derived a new experimental value for the proton charge radius that is ten times more precise than the accepted official CODATA (the Committee on Data for Science and Technology) value, but about 4% smaller than expected. This 'proton size puzzle' has stirred intense discussions and is stimulating plans for future precision experiments. The discrepancy may be due to some mistake, or it may hint at a dent in the theory of quantum electrodynamics.

Can the performance of the optical frequency comb technique be improved?
Yes. A precise time measurement, for instance using optical lattice clock, can improve the performance of the optical frequency comb technique. Optical clocks based on a single trapped ion need a lengthy time-consuming process to reach a fractional uncertainty of around 10^{-17}. Lattice clocks could shorten this time considerably, which would be of interest for high-speed communication and more precise space–time measurements by global positioning systems. A novel device that senses small changes in gravitational potential could be developed to explore the molten core of the earth. Geologists could gain unexpected knowledge using this technique, which is an exciting prospect. Another challenge is to miniaturize the optical frequency comb system to expand its versatility. Tobias Kippenberg and Pascal Del'Haye are now tackling this issue in our laboratory by fabricating toroid-shaped optical microresonators. In such a small system, one can create frequency combs that can span an optical octave by building up circulating power and employing cascaded four-wave mixing. I think it's quite a promising approach, particularly as the fabrication of integrated microresonators on chips using silicon nitride is now becoming more practical. For some applications to be practical, the size of the laser source system must be very compact.

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