With a fine-tooth comb

The tool of choice to measure optical frequencies with extremely high precision is the optical frequency comb. Camille-Sophie Brès explains what makes this technique so powerful.

Like many natural sciences, laser physics is all about accuracy and precision. Arthur Schawlow, the 1981 Nobel Prize winner in physics, wisely advised to “never measure anything but frequency”; the optical frequency comb (OFC) can therefore be considered the most exquisite frequency ruler. This year marks the 60th anniversary of the demonstration of the first laser mentioned in this issue’s *Editorial*. The field of laser physics initiated by Theodore Maiman’s experiment has since then produced a wide variety of specialized lasers, which have revolutionized science and society. Although the OFC is slightly younger than the laser, it has already benefited from close to two decades of development and its story dates back to even a few years before that.

But what precisely is an OFC? In the original sense, it is a phase-stabilized mode-locked laser. Such a laser, whose very first prototype was developed in 1964, produces a continuous train of extremely short light pulses with a duration of the order of pico- or femtoseconds. While lasing action forces the emission of photons with the same energy and thus the same frequency, not all lasers are monochromatic: the generation of ultra-short pulses requires that a large number of these cavity modes interfere coherently. As such, a mode-locked laser contains millions of resonant frequencies with a fixed-phase relationship between them. However, there are different mechanisms that can also generate OFCs, such as electro-optic modulation or four-wave mixing in nonlinear media. Therefore, the OFC is better described in the frequency domain: the spectrum consists of an equally spaced series of discrete and sharp frequency lines — resembling the teeth of a comb (pictured).

The optical frequency components (or modes) of such a light source are therefore characterized by the frequency separation between the teeth of the comb, typically in the microwave range, and a common offset, which fully expresses the modes of the OFC. This means that the microwave frequencies completely define the optical frequencies. Therefore, the OFC

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directly converts optical frequencies in the terahertz range to microwave frequencies in the megahertz to gigahertz range. Thanks to this amazing feature, OFCs became popular in 1999 as they provided a solution to exploit the full potential of optical atomic clocks¹.

Despite the fact that the predicted accuracy improvement of clocks based on optical transitions in atoms has been long recognized, measurements of such optical signals faced a fundamental problem because light oscillates around a million times faster than state-of-the-art electronics. The potential gains were thus lost in the limited accuracy of the available measurement techniques. Enter the OFC, used as a ‘gear’: the regularly spaced teeth of the comb divide the oscillations of the optical clock by the number of teeth — typically between 10^5 and 10^6 — transferring the signal to the lower frequencies of the microwave domain. These oscillations can then be counted using standard microwave techniques. As a result, optical clocks now allow for a fidelity better than 1 part in 10^{18} — a two-orders-of-magnitude improvement compared to microwave clocks. This fundamental advancement in precision spectroscopy² earned Theodor Hänsch and John Hall half the Nobel Prize in physics in 2005.

The OFC’s astonishing performance as a frequency ruler with a 19-digit accuracy might not be entirely obvious to everyone,

but the tool has also become valuable in a wide range of applications, from use as a source for high-speed optical communication to the detection of chemicals, or employed for measuring distances. It is not only in its applications that the OFC is evolving but also as a system, moving away from tabletop designs to smaller and easier to use integrated structures³. Despite still being at the research stage, such chip-size devices flaunt the attributes of compactness, robustness and simplicity required for commercial applications.

So, is the OFC following the path of the laser? After 60 years of development, lasers are now omnipresent in the most advanced scientific complexes but also in our homes and often in the smart watches on our wrists. It is fair to assume that laser scientists will not let the OFC rest until they have combed through all domains. □

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Published online: 7 May 2020

<https://doi.org/10.1038/s41567-020-0895-8>

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