Electro-optic combs raise above the noise

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Perspective on *Ultrafast electro-optic light with subcycle field control*
By David R. Carlson et al.

Electro-optic combs raise above the noise

Electro-optic modulation of light can have a precision equivalent to one optical-field cycle

Victor Torres-Company

Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Gothenburg, Sweden. Email: torresv@chalmers.se

Lasers typically emit light at one frequency, but some are engineered to emit light at a set of evenly spaced optical frequencies that maintain a stable phase relation, as if a myriad of lasers were radiating in unison. Most of these laser frequency combs are based on mode- locked lasers that deliver ultrashort light pulses in a repetitive manner. This approach has found use in attosecond physics, optical clocks, molecular spectroscopy, and the generation of ultrastable microwaves (*1*). Before the advent of the mode-locked frequency comb (*2*, *3*), the electro-optic modulation method (*4*) was a popular technique for measuring frequency differences between lasers (*5*). On page 1358 of this issue, Carlson *et al.* (*6*) report that electro-optic modulation of light can be used to create an ultrafast laser source for the generation of frequency combs. The "comeback" of this method is part of a larger set of efforts exploring alternative techniques for creating frequency combs to enable new applications and facilitate their operation outside the laboratory (*7*).

Mode-locked lasers consist of a cavity that contains an optical amplifier and an optical element that favors the formation of pulses (*8*). Dramatic progress in ultrafast optics and specialty optical fibers in the 1990s allowed the bandwidth of mode-locked lasers to be expanded to one octave (that is, the optical frequency on the blue side of the spectrum is twice the frequency on the red side), as well as the stabilization of the location of the optical frequencies with unprecedented accuracy and precision (*2*, *3*). Nonetheless, such mode- locked laser implementations can suffer from some disadvantages, such as limited tuning of the spacing between lines in the comb.

Electro-optic modulation offers potential advantages for frequency comb generation, one being its simplicity (see the figure). The input laser defines the central frequency of the comb, and a modulator driven by a microwave signal sets the distance between consecutive frequencies. Thus, a comb of optical frequencies can be produced by piggy- backing optoelectronic components formerly developed for telecommunications applications. Consecutive lines in an electro-optic comb can be easily set apart by 10 GHz or more (*9*), an aspect that is notably challenging to achieve with mode-locked lasers (*10*). A critical issue with electro-optic combs has been finding ways of expanding their band- width while keeping the comb-like structure. The spectral purity of the optical sidebands degrades the further away they are from the central line because of the accumulation of microwave noise. The degradation for the lines near the center is barely noticeable, but when the spectrum spans an octave, the comb structure is almost washed out by noise. This problem cannot be solved even by using the purest microwave signals available (*11*).

Carlson *et al.* took advantage of key advances in ultrafast nanophotonics and microwave engineering to suppress this detrimental noise. They achieve a true optical frequency comb spectrum derived from an electro-optic source by forcing the micro- wave signal to follow the laser, using optical and microwave filtering to suppress the noise, and broadening the spectrum to form few-cycle optical pulses. Their study unravels the fundamental origin of the noise formation in electro-optic frequency combs and paves the way for technological innovations that could benefit from advances in integrated modulators (*12*) and resonant nonlin- ear optics (*13*). Their frequency comb extends beyond the octave while keeping the width of the frequency lines below 1 Hz. This light source delivers optical pulses shorter than 20 fs in duration at a 10-GHz repetition rate with a timing precision better than one pe- riod of the oscillating electric field.

Such a remarkable accomplishment brings the performance of electro-optic combs to a level that allows meaningful comparisons with mode-locked frequency combs. The light source by Carlson *et al*. is not meant to replace the latter, but rather to enable appli- cations that benefit from the combination of ultrafast repetition rate and timing precision. Possibilities for future applications are only limited by our imagination, and range from calibration of astronomical spectrographs for the search of Earth-like exoplanets (*14*) to impulsive Raman scattering microscopy (*15*).

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