Searching for applications with a fine-tooth comb

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Frequency combs — broadband phase-coherent optical sources — are finding an increasing number of new applications in the field of metrology.

A frequency comb is the optical spectrum formed by an ideal regular train of optical pulses and comprises a series of repeating, equally spaced spectral lines. Like many ground-breaking technologies, frequency combs are simple in concept. It is particularly remarkable that this simple concept can be realized in a number of different experimental systems to create a precise 'frequency ruler'. The primary motivation for the development of the frequency comb was to compare optical clocks with other radiofrequency (RF) standards or clocks. Frequency combs have excelled at this task and can support comparisons at fractional uncertainties of 10^{-19} or lower, limited only by the Doppler shifts associated with the thermal contraction or expansion of the experimental apparatus[1–3].

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However, the utility of frequency combs is not limited to optical clocks. They provide a broadband optical source with well-defined phase coherence across the spectrum and are being explored for a growing number of applications. This Commentary will touch on a few of the metrological applications of frequency combs while omitting their impact in other research areas, such as for developing attosecond laser sources[4]. Many review articles provide a more complete discussion of frequency combs, including the 2005 Nobel lectures of Hänsch and Hall[5–8].

A frequency comb can be generated by modulating a continuous-wave laser with a stable RF source to create multiple equidistant sidebands, or 'comb teeth' (Fig. 1). This type of comb is well-suited to telecommunications applications and arbitrary waveform generation, but has limited bandwidth coverage. Combs of much broader bandwidth are realized by the use of passively mode-locked lasers. One might expect that various noise processes would disrupt the pulse train of a mode-locked laser, effectively blurring out any frequency comb structure. Fortunately, it turns out that this noise simply causes the comb to stretch or shift. This motion can be eliminated by phase-locking (or 'monitoring') the comb with respect to an underlying frequency reference[1–3,5–8] to stabilize the pulse repetition rate (f_r), which controls the tooth spacing, and the carrier–envelope offset frequency (f_{ceo}), which sets the overall frequency shift of the comb. The teeth of the resulting comb are phase-coherent with each other as well as with the underlying frequency reference.

This broadband phase-coherence distinguishes frequency combs from conventional laser sources and underlies all of their true metrological applications; comb tooth frequencies are not approximate but rather are exactly known with respect to the reference. As a phase-locked system, the frequency comb is more like an RF oscillator than a conventional laser; its performance is often better assessed by the residual phase noise rather than the linewidth. In fact, for a state-of-the-art frequency comb locked to an optical reference such as a cavity-stabilized laser, the spectrum of each comb tooth approaches a delta function, with a residual linewidth limited only by the observation period. Fortunately, for many practical applications, a much lower level of performance is adequate and results in a simpler overall system. Figure 2 depicts some of the more popular metrology-oriented applications, which are discussed below, along with an indication of the important comb attributes.

Optical clocks

Spectroscopy is one of the most basic applications of frequency combs in optics. Their most dramatic role in spectroscopy is for the frequency metrology of optical clocks, which is the precise relative measurement of lasers locked to different ultranarrow atomic transitions. Combs are also important for the accurate measurement of many other atomic and molecular lines outside of optical clocks[9,10], as they are the only straightforward tool capable of accurate optical frequency metrology from the 10^{-17}-level associated with optical clocks all the way up to the 10^{-8} fractional accuracy of conventional wavelength meters.

Comb-calibrated tunable lasers

In the previous precision spectroscopy example, a laser is locked to the transition of interest and the comb is then used to measure the fixed laser frequency. However, metrology of a fixed laser frequency alone is somewhat limiting. Frequency metrology with combs was recently extended to the calibration of rapidly tunable lasers[11–13], such as those used for broadband spectroscopy or optical component metrology. Tunable lasers have conventionally been calibrated against an etalon and/or a gas cell, but calibration to a comb can provide a 1,000-fold or higher improvement in precision and accuracy. Unfortunately, current comb-calibrated tunable lasers are considerably more complex than conventional set-ups; their full implementation requires the development of a compact, inexpensive comb — a trait shared by many applications beyond optical clocks.

Astronomical spectrograph calibration

Combs are also being explored as broadband calibration sources for astronomical spectrographs. Astronomical spectrographs have the remarkable

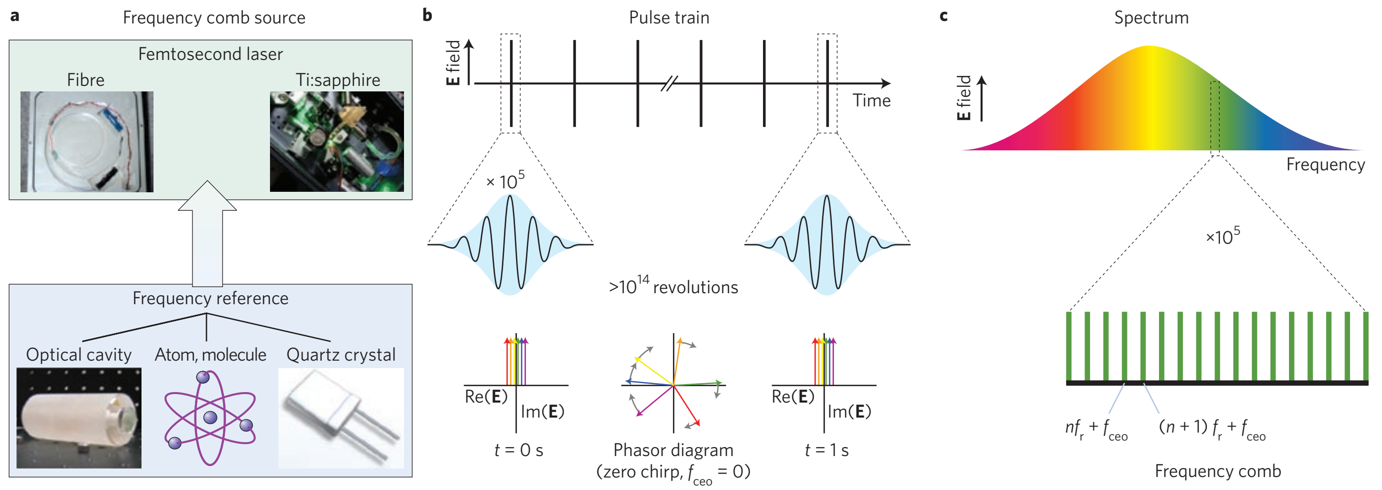

Figure 1 | Frequency combs come in many shapes and sizes. **a**, Commonly used passively mode-locked Ti:sapphire or erbium-fibre femtosecond lasers, which produce a comb when stabilized to an underlying frequency reference. Ti:sapphire femtosecond laser image in **a** courtesy of Scott Diddams. **b**, The output pulse train has a regular period and a well-defined relative phase from pulse to pulse, as emphasized by the lower diagrams, in which the phasors across the spectrum align again almost exactly for every pulse, with a jitter determined by the comb's residual phase noise. **c**, The output spectrum of a frequency comb is broad and comprises millions of comb teeth. The laser output is often further spectrally broadened in highly nonlinear fibre (not shown) to allow self-referenced phase-locking or to reach a specific frequency. In that case, although the pulses become heavily distorted in time, their phase profile is reproduced from pulse to pulse. The spectrum also becomes strongly distorted in amplitude, but the teeth frequencies remain absolutely fixed to the frequency reference.

short-term stability needed to measure the extremely small Doppler shifts resulting from planets orbiting distant stars or potentially the slow change in the cosmological red-shift[14]. However, even the best spectrographs are optomechanical systems and therefore require periodic calibration, which is currently performed using atomic vapour lamps. Broadband combs can function as astronomical calibration sources with high accuracy, great spectral range and with nearly perfect long-term stability. Combs developed for this purpose have gained the catchy moniker of 'astrocombs'. The challenges are to develop combs with repetition rates high enough such that individual comb teeth can be resolved by the spectrograph, and to successfully incorporate these combs into large, complex telescopes. Astrocomb systems are currently being installed in a few telescopes around the world for preliminary demonstration experiments.

Comb spectroscopy

The previous three examples use a frequency comb to enhance a conventional spectroscopy set-up by providing a frequency axis for the laser source or spectrometer. In another approach, combs can be used to interrogate a sample directly. Direct-comb spectroscopy brings a number of benefits, including a spectral coverage potentially larger than that available using tunable lasers, a collimated single-mode beam, and teeth that can be coupled to a matched cavity for long effective path lengths[15]. Ignoring these benefits and taking a purely metrological viewpoint, the true frequency accuracy and precision of a frequency comb are exploited only if its individual comb teeth are resolved after transmission through the sample. Several methods have been demonstrated that achieve this goal. At wide tooth spacings (achievable with Ti:sapphire combs), individual comb teeth can be resolved with a high-resolution 'VIPA' spectrometer[16]. At lower tooth spacings, the comb teeth can be resolved through a Vernier approach with either a mismatched resonant cavity[17] or by heterodyne detection against a second frequency comb with an offset repetition rate[18–20]. Although heterodyne detection requires two combs, the simplicity of the detection process means that this technique will have promise for precision spectroscopy across the mid- and far-infrared, once appropriate combs have been developed. Although direct-comb spectroscopy has mostly focused on producing basic demonstrations that illustrate sensitivity and selectivity, it also has potential for the precise metrology of molecular line shapes, which are interesting both for the study of collisional physics and for accurate measurements of gas concentrations relevant to climate change.

Frequency/time transfer

The phase coherence and broad optical bandwidths of frequency combs can be exploited for frequency transfer and timing synchronization across fibre networks. Here, a coherent optical frequency comb translates the optical clock frequency to a phase-coherent 1.5 μm continuous-wave laser. This laser signal is then transmitted over long distances of a Doppler-compensated optical fibre to a remote frequency comb, where its frequency is translated to either a second optical frequency or the RF domain, depending on the application[2,21]. Fractional frequency uncertainties of 10^{-19} are achievable over hundreds of kilometres, allowing for the faithful dissemination and comparison of state-of-the-art optical clocks. Time transfer, as opposed to frequency transfer, is a more challenging task that has yet to be demonstrated in a comb-based system. However, timing synchronization across a local network, for example in a free-electron laser accelerator system, has indeed been demonstrated at sub-10-fs levels by exploiting the precise timing of the pulse train from a frequency comb source[22].

Low-phase-noise microwaves

An original impetus for the development of self-referenced frequency combs was to multiply the frequency of RF clocks up to the optical domain. Frequency combs can also be operated in the reverse direction, dividing the optical domain down to the RF regime. This technique is the basis for low-phase-noise microwave generation and arbitrary RF waveform generation. For low-phase-noise microwave generation, a self-referenced frequency comb is phase-

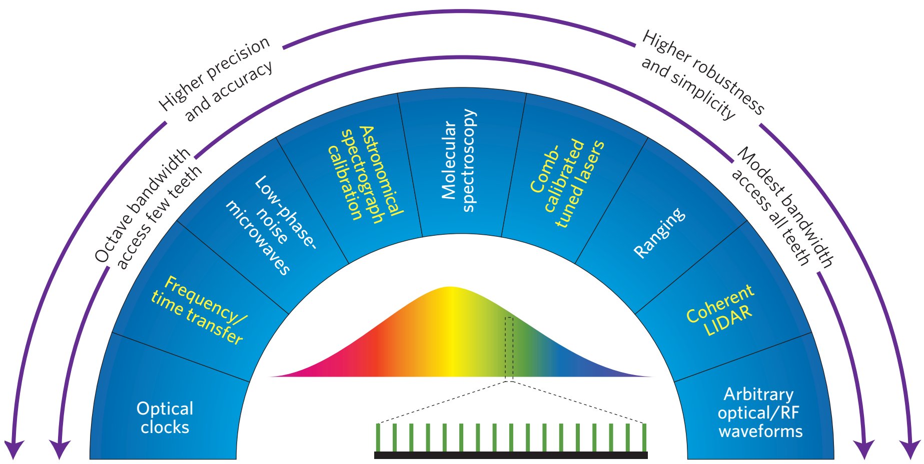

Figure 2 | Some of the metrological applications of frequency combs. Combs are quite mature for optical clock applications but are in an exploratory phase for some of the other applications listed here. The arrows across the top indicate the relative importance of frequency comb attributes in terms of precision, accuracy, robustness, simplicity, spectral coverage and number of comb teeth exploited in a particular application. For example, optical clocks use only a few of the many comb teeth available — those near the optical clock laser frequency. However, molecular spectroscopy uses many more comb teeth (those across the molecular lines of interest), and ranging or arbitrary optical/RF waveform generation use all the comb teeth.

locked to a continuous-wave laser that is itself phase-locked to a high-finesse optical cavity. In the limit of perfect phase-locking, the comb's repetition rate is then a fraction of the continuous-wave laser frequency, with the phase noise given by the intrinsic thermal cavity noise. Photodetection of the comb repetition rate or its harmonics generates a microwave signal with a close-in phase noise lower than that achieved with room-temperature dielectric RF oscillators[23]. These low-phase-noise microwaves can support sensitive Doppler RADAR and precision microwave interferometry measurements.

Ranging and coherent LIDAR

It is not surprising that combs have also been used for precision ranging, given the interrelated nature of time, speed and distance. As with spectroscopy, frequency combs can support conventional laser ranging approaches by functioning as a precise spectral ruler[24]. Frequency combs can also be used directly through approaches that mirror multiwavelength interferometry or time-of-flight measurements[25,26]. The accurate, precise timebase of frequency combs allow them to function not only as a spectral ruler, but also as a spatial ruler, with an accuracy limited only by variations in the index of refraction over the measurement path. All comb-based ranging systems exploit specular reflectors because the power in each comb tooth is too low to compete with a continuous-wave laser. Therefore, in the case of coherent light detection and ranging (LIDAR) to a diffuse target, the more appropriate use of a comb may be to calibrate it against a fast tunable laser[12,13]. Applications of frequency combs in vibrometry, synthetic-aperture or parallel multistatic coherent LIDAR remain largely untapped, again in part owing to the lack of truly compact, environmentally robust devices.

Arbitrary optical/RF waveforms

Coherent LIDAR is also a motivation behind the generation and metrology of arbitrary optical waveforms[27]. The objective here is to modulate the individual teeth of a frequency comb with a specific phase and amplitude profile to generate an arbitrary optical waveform. Detection of this optical waveform can also be used to generate an arbitrary RF waveform while avoiding the usual limitations imposed by digital-to-analog converters. Finally, the ability to generate arbitrary optical waveforms would permit coherent excitation of atoms or molecules well beyond today's demonstrations, which have so far been limited by the relatively simple comb structure available to Raman or two-photon transitions.

Conclusion

This myriad of applications has put an ever-increasing burden on the performance of optical combs, requiring, for example, low phase noise, high repetition rate, high power, wide spectral coverage and, most importantly, great robustness in terms of simplicity, compactness and environmentally stable mode-locking, phase-locking and monitoring. Although fibre-based combs are significantly more robust than Ti:sapphire combs and can operate continuously for years, they still do so only in a laboratory environment. The many desired improvements to frequency combs are well-recognized, and the basic technology remains an active area of research[28,29]. As with any technology, it seems likely that combs and their applications will advance hand-in-hand over the coming years. It will be interesting to see which of the existing applications will survive and flourish, and what new ones will arise. ❐

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