TECHNOLOGY

The art of illumination

In November 2006, the Yamaguchi Prefectural Art Museum in southern Japan held an exhibition entitled 'The Trip to Sesshu'. It commemorated the 500th anniversary of the death of the Zen Buddhist monk and painter Sesshu Toyo, whose delicate *suibokuga* ink paintings have been designated 'National Treasures' by the Japanese government.

So that visitors could appreciate Sesshu's scrolls as closely as possible to the way original admirers did — under candlelight or torchlight — some of the paintings were illuminated by a specially designed light-emitting diode (LED) system. Tsunemasa Taguchi and Michitaka Kono now provide the technical details of that system (T. Taguchi and M. Kono *J. Light Visual Environ.* **31,** 149–151; 2007).

LEDs are solid-state light emitters known for their energy efficiency, flexibility of design and robustness. For a long time, they were made to emit light only in a particular part of the visible-wavelength spectrum. But in the mid-1990s a new generation emerged, based on blue LEDs covered with a yellow phosphorescent layer, which emitted bright, white light.

Taguchi and Kono's lighting system used special LEDs that contained three different phosphors, each emitting at different frequencies. This meant that the white light emitted had a particularly high colour quality, as quantified on a scale known as the colour-rendering index. To optimize viewers' appreciation, the authors tailored the LEDs to render the earthy red colours characteristic of the antique scrolls especially well.

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The individual lights were positioned so as to distribute light evenly on the artwork (first two paintings pictured), rather than scattering it around them as fluorescent lamps would do (paintings in background). The output of the LEDs was stable and did not cause heating, thus assisting preservation of the precious scripts.

White LEDs are becoming ever brighter, more efficient and less expensive. As a result, traditional light bulbs are increasingly on the way out. Large-scale applications, such as car lights, traffic signals and Christmas decorations, are where the economic benefits of LED use are being felt. But the illumination of antique Japanese art must surely rank as one of the diodes' most aesthetically pleasing applications.

Liesbeth Venema

the spatial clustering of synapses with similar firing patterns. Thus, for some forms of activity-dependent plasticity in the hippocampus, the fundamental unit of regulation might be larger than an individual synapse[9], and rather a physically clustered cohort of synapses with similar firing patterns, whose spatial arrangement on dendrites arises naturally following mutually reinforcing interactions between synapses.

It is neuroscientists' goal to understand the plastic features of the brain that make storing memories and learning new behaviours possible. In trying to achieve this formidable goal, many neuroscientists hope that, by uncovering the mechanisms behind the regulation of individual synapses, they will reveal the rules that govern the wiring of the brain. Harvey and Svoboda's results introduce a new level of complexity. They demonstrate that these rules vary across distances as short as a few micrometres, and are themselves altered on a minute-by-minute time frame. ■

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METROLOGY

New generation of combs

Steven T. Cundiff

To measure an optical frequency, you are best off using an optical frequency comb. A radical approach shakes up how these combs are produced, and will permit their closer integration into optical-fibre technology.

Increasing the range over which frequencies can be accurately measured is an exertion driven both by applications (making sure that a mobile phone uses the right channel, for instance) and by fundamental physics: time and frequency are the most accurately measured physical quantities, and thus are often used in tests of theories such as relativity and quantum mechanics. Optical frequency combs[1,2] — arrays of regularly spaced, well-defined reference frequencies — have revolutionized these endeavours[3,4]. Optical atomic clocks using this form of benchmarking can be more precise[5] than the very best clocks referenced to the current caesium atomic time standard, and combs are increasingly being used for sensitive and rapid detection of molecular processes[6]. The growing importance of the technique was recognized by its appearance in the citation for the 2005 Nobel Prize in Physics[7].

On page 1214 of this issue, Del'Haye *et al.*[8] describe the creation of an optical frequency comb using a toroidal glass microresonator. The very strong light fields produced drive the optical response of the glass into the nonlinear regime, where the principle of wave superposition no longer applies and waves can mix with one another to create new frequencies. The flexibility and small size of this apparatus give it huge potential for use in diverse areas, from telecommunications to astrophysics.

Frequency combs provide a way of accurately measuring frequencies that are too high to be measured directly. At radio frequencies, combs are produced by driving an electrical element, typically a step-recovery diode, with a simple, sinusoidal input signal. Once this sine wave exceeds a threshold, the diode converts it into a square wave, which contains new frequencies. The highest frequency is determined by the switching time, and is around 100 picoseconds for the best diodes. The standardized comb frequencies thus generated are integer multiples (harmonics) of the well-known input-wave frequency.

Generating a comb with a useful frequency spacing at optical frequencies requires a different approach. Until a few years ago, this meant injecting light from a continuous-wave laser into an optical cavity containing an electro-optic modulator driven by a radio-frequency signal[9]. The result was a cascade of evenly spaced frequency lines above and below the laser's optical frequency, corresponding to adding or subtracting integer multiples of the radio-frequency modulator signal, with each line generating the next. Combs generated in this way generally spanned a frequency range of several terahertz.

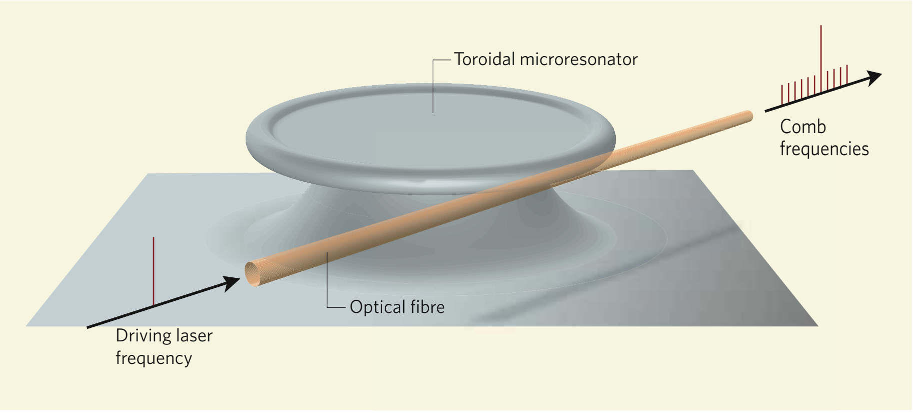

Figure 1 | Unfurling the standard. The high 'quality factor' of the toroidal microresonator used by Del'Haye *et al.*[8] allows a driving laser field to be held for a long time, greatly increasing the light intensity to the point at which the response of the resonator's glass becomes nonlinear. When a continuous wave laser, corresponding to a single, well-known frequency spike (left), is launched into this microresonator, its light is converted into a regularly spaced comb of frequencies (right) through its interaction with the wave modes of the resonator cavity. Such combs allow frequencies to be measured accurately over a wide range of frequencies (in this case optical), as each 'tooth' acts as a reliable frequency standard.

The philosophy changed in the year 2000, with the advent of femtosecond (10^{-15} s) optical frequency combs[1,2]. These combs are produced by mode-locked lasers whose light comes in short, sharp bursts of femtosecond duration. A train of such short pulses can be decomposed into light at the laser's offset frequency (the rate at which its phase evolves) plus integer multiples of the laser's repetition rate (the number of pulses produced per second). The shorter the pulse, the wider the frequency spectrum spanned by these frequency lines. Under the right conditions, a spectrum spanning hundreds of terahertz — broad enough to cover the entire visible spectrum, and thus look white to the eye — can be produced.

The breadth of the band is crucial, because most methods for measuring the offset frequency use a self-referencing technique that requires a spectrum spanning an octave (a factor of two in frequency)[10]. The great advantage of the femtosecond-laser approach is that it locks the phases of all comb lines together. By contrast, the electro-optic modulator locks the phases only of adjacent comb lines, allowing phase variations to build up towards the edges of the comb, which limits the precision of any frequency measurement there.

In some ways, the new approach to optical-frequency generation taken by Del'Haye *et al.*[8] is similar to older radio-frequency techniques. Like the radio-frequency approach, it takes a sinusoidal input signal — the output of a continuous-wave laser at a wavelength of 1,550 nanometres — and couples it to a nonlinear response medium, in the form of a toroidal microresonator[11]. This microresonator stores up the laser light, greatly increasing its intensity as more and more light enters such that nonlinear wave mixing occurs. The frequencies of the output lines from the microresonator are equally spaced on either side of the frequency of the input laser light, with a spacing determined by the properties of the microresonator (Fig. 1).

The nonlinear generation of a pair of frequency lines either side of an optical signal is not new. The generation of tens of them is, and Del'Haye *et al.* achieve it by using a microresonator with a very large 'quality factor' — a measure of the sharpness of its resonant response. This not only enhances the resonator's nonlinearity but also produces a cascading effect, with each frequency line generating the next, just as in the electro-optic comb.

For a spectral comb to be useful as a frequency reference, the spacing of the comb lines must be perfectly even, and the lines themselves must be narrow. Conservation of energy and momentum show why the spacing of lines in a toroidal microresonator must be even: in the initial nonlinear response, two 'pump' photons of frequency ν_p are destroyed to generate one photon in each of the sidebands. These have frequencies ν_+ and ν_-, which are related by $2\nu_p = \nu_+ + \nu_-$, according to energy conservation. This allows a continuum of frequencies; momentum conservation, which expresses itself as the requirement that the phase evolution of the two lines be matched, then selects out one pair of frequencies for the first two lines. Once the initial pair of lines is generated, the cascade that then builds up preserves their spacing.

By comparing the comb generated by a microresonator to a femtosecond comb, Del'Haye and colleagues demonstrate that the spacing is indeed regular, to better than one part in 10^{-17}, rivalling the quality of femtosecond combs[12]. The implication, although not yet definitely proved, is that the comb lines are narrow, and thus phase noise is not building up significantly in the nonlinear cascade.

An obvious advantage of the new device is its small size and potential for integration with optical-fibre technology. But the offset frequency of the comb being determined by the frequency of the pump laser is a double-edged sword: if the laser frequency is known and stable, it is an advantage; if it is unstable, it is a disadvantage. If the frequency of the pump laser is not known, it can be determined using the same self-referencing technique used to determine the offset frequency in a femtosecond comb. This technique is easiest to apply if the width of the comb is pushed to cover an octave (in Del'Haye and colleagues' set-up[8] it is already close).

Probably the biggest obstacle to using the authors' comb for optical-frequency metrology is the spacing of its teeth, which is around 1 terahertz. The ideal comb spacing is of the order of the detection bandwidth, which is typically a few gigahertz — a factor of around 1,000 smaller. Femtosecond combs produced by mode-locked lasers typically have a tooth spacing of 100 megahertz to 1 gigahertz. This very tight spacing is also less than ideal, because it reduces the power per comb line, but the spacing can be increased by filtering out a subset of the comb lines. Lowering the spacing of the microresonator combs to this value will be a challenge: it would require increasing the diameter of the toroid to about 0.5 mm, while preserving its extraordinarily high quality factor and simultaneously increasing the laser power to around 5 watts to maintain the nonlinear effect. Overcoming such problems will make for interesting times for this exciting new comb technology. ■

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Correction

The photograph accompanying the obituary of Arthur Kornberg by Tania A. Baker (*Nature* **450,** 809; 2007) was inverted left-to-right. Here is the picture in the correct orientation. It shows Dr Kornberg, his first wife Sylvy, and a model of the DNA double-helix (now right-handed, not left-handed).