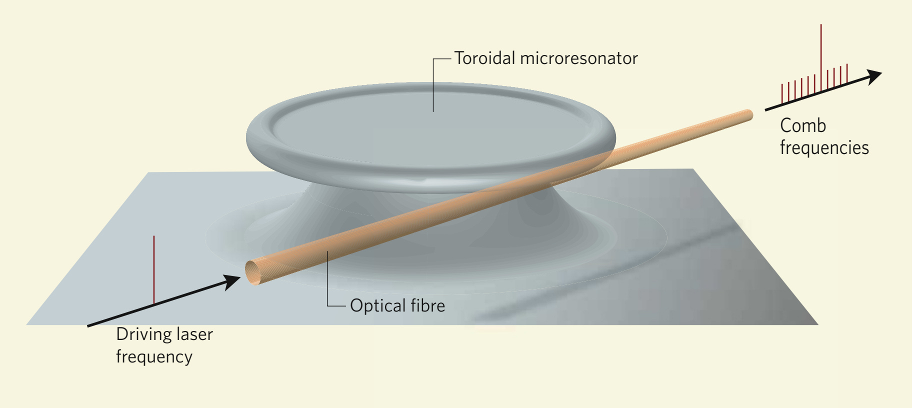

Figure 1 | Unfurling the standard. The high 'quality factor' of the toroidal microresonator used by Del'Haye *et al.*[8] allows a driving laser field to be held for a long time, greatly increasing the light intensity to the point at which the response of the resonator's glass becomes nonlinear. When 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. ■

Steven T. Cundiff is at JILA, National
Institute of Standards and Technology,
University of Colorado, Boulder,
Colorado 80309-0440, USA.
e-mail: cundiffs@jila.colorado.edu

1. Jones, D. J. *et al. Science* **288,** 635–639 (2000).
2. Holzwarth, R. *et al. Phys. Rev. Lett.* **85,** 2264–2267 (2000).
3. Cundiff, S. T. & Ye, J. *Rev. Mod. Phys.* **75,** 325–342 (2003).
4. Udem, Th., Holzwarth, R. & Hänsch, T. W. *Nature* **416,** 233–237 (2002).
5. Ma, L. S. *Opt. Photon. News* **18**(9), 42–47 (2007).
6 Thorpe, M. J., Moll, K. D., Jones, R. J., Safdi, B. & Ye, J. *Science* **311,** 1595–1599 (2006).
7. http://nobelprize.org/nobel_prizes/physics/laureates/2005/index.html (2005).
8. Del'Haye, P. *et al. Nature* **450,** 1214–1217 (2007).
9. Kourogi, M., Nakagawa, K. & Ohtsu, M. *IEEE J. Quantum Electron.* **29,** 2693–2701 (1993).
10. Telle, H. R. *et al. App. Phys. B* **69,** 327–332 (1999).
11. Armani, D. K., Kippenberg, T. J., Spillane, S. M. & Vahala, K. J. *Nature* **421,** 925–928 (2003).
12. Ma, L.-S. *et al. Science* **303,** 1843–1845 (2004).

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).