FREQUENCY COMBS

Cavity solitons come of age

The generation and manipulation of cavity solitons in microresonators is creating new opportunities for Kerr combs to aid applications such as optical communications and spectroscopy.

Andrew M. Weiner

Mode-locked lasers, first explored around 50 years ago, have become much valued sources of femtosecond pulses and are exploited for a wide range of applications spanning materials processing to metrology. A little more than 15 years ago, self-referencing of such lasers led to the advent of optical frequency combs in which the broadband optical spectrum of their output is carved into series of precisely spaced delta functions with stabilized absolute frequencies[1]. Within a few years, such combs had revolutionized the precision and accuracy with which different optical transition frequencies can be measured and compared, an advance celebrated by the 2005 Nobel Prize in Physics. However, the use of mode-locked lasers brought several limitations. First, their repetition rate (which determines the spacing of the comb lines) is too low for some applications. Second, although such lasers are much smaller than frequency divider chains previously employed, they are still too bulky for many applications outside the laboratory.

A new approach to comb generation appeared on the scene in 2007, when continuous-wave (CW) pumping of a high-quality-factor microresonator was observed to result in formation of combs of optical frequencies spaced by hundreds of gigahertz[2]. Such combs arise due to nonlinear wave mixing mediated by the optical Kerr effect and are frequently termed Kerr combs. After a few years, researchers realized that although very broad bandwidth Kerr combs could be attained, they were generally plagued by incoherence and high noise[3]. Subsequent efforts then demonstrated paths to mode-locked operation, in which the incoherence and noise drop out[4]. In a particularly interesting mode-locked state, the comb comprises cavity solitons (more formally called dissipative Kerr solitons) — ultrashort pulses of light that propagate in the microresonator with remarkable stability thanks to a double balance between loss and parametric gain and between dispersion and nonlinearity[5].

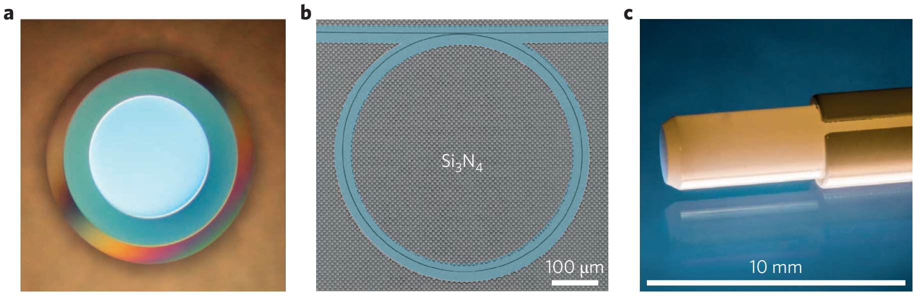

Figure 1 | Microresonators. **a**, Silica wedge whispering-gallery-mode resonator[9], similar to the resonator with 3 mm diameter and 22 GHz free spectral range (FSR) used in the experiments of Yang and colleagues[7]. **b**, Silicon nitride microring resonator with integrated coupling waveguide, ~100 GHz FSR, used in the experiments of Marin-Palomo and co-workers[6]. **c**, Fibre-based Fabry–Pérot resonator with ~10 GHz FSR used in the experiments of Obrzud and colleagues[8]. Figure reproduced from: **a**, ref. 9, **b**, ref. 6, **c**, ref. 8, Macmillan Publishers Ltd.

Progress in combs based on cavity solitons is advancing rapidly and is growing increasingly sophisticated. This trend is exemplified beautifully by the publication of three recent papers in the area in *Nature* and *Nature Photonics*. Writing in *Nature*, Marin-Palomo *et al.* report[6] impressive wavelength-division multiplexed lightwave communication experiments in which the cavity-soliton-based combs provide up to 179 distinct optical carriers that can be individually encoded with data, supporting an aggregate transmission rate beyond 50 Tb s^{-1} over a 75 km span of fibre. Meanwhile, in this issue of *Nature Photonics*, Yang *et al.* describe the generation of pairs of cavity solitons locked in phase and counter-propagating in a single microresonator with potential impact for dual-comb spectroscopy[7], and Obrzud *et al.* discuss experiments in which pumping of a microresonator with an externally generated comb triggers formation of much shorter (femtosecond scale) cavity solitons[8].

Kerr combs have been demonstrated in many different material platforms and resonator geometries (Fig. 1; showing images of the resonators employed in refs 6–8). The counter-propagating cavity soliton experiments[7] use a silica wedge resonator[9] (Fig. 1a) with ~22 GHz free spectral range (FSR), which corresponds to trains of cavity solitons repeating every 46 ps. Such structures, which typically have quality factors exceeding 10^8 and rely on a closely spaced tapered optical fibre (not shown) for coupling, are representative of whispering-gallery-mode resonators — a class of resonators also employed in the first experiments to demonstrate Kerr combs[2].

The communication experiments reported by Marin-Palomo *et al.*[6] exploit a microring resonator structure with ~100 GHz FSR fabricated in a silicon nitride film on a silicon substrate (Fig. 1b). Microrings have the advantage of an on-chip geometry similar to other integrated photonics with stable coupling structures (such as the straight 'bus' waveguide evident in the image), but usually exhibit lower quality factors on the order of a few times 10^6 (which leads to higher pump-power requirements). Obrzud *et al.* introduce the use of a fibre-based Fabry–Pérot resonator for Kerr comb generation[8]. The resonator consists of an ~1 cm length of single-mode fibre with dielectric mirror coatings deposited onto its facets, mounted inside a fibre-optic ferrule, allowing connection to standard fibre connectors (Fig. 1c). The fibre-based resonator provides

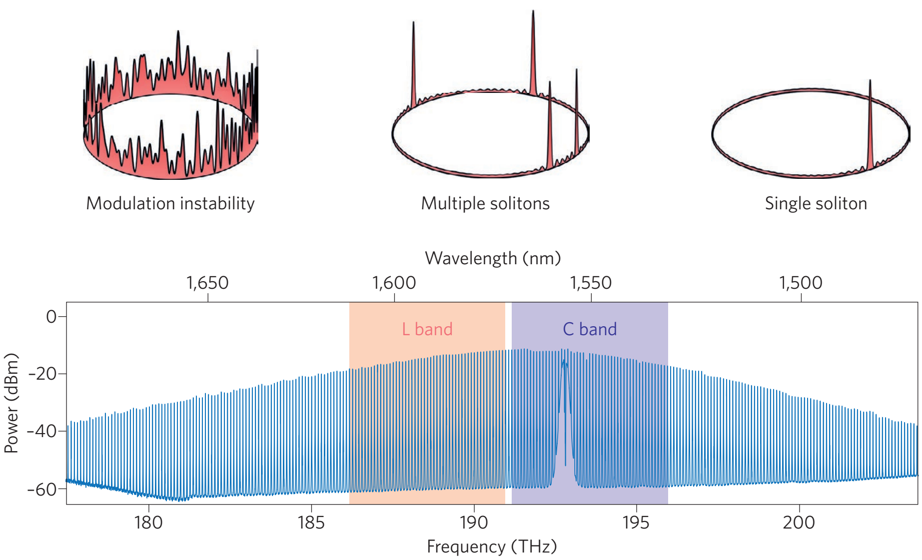

Figure 2 | Formation of cavity solitons. Top: evolution of a comb field from a noisy modulational instability stage to a stable operating regime supporting multiple cavity solitons first, which is eventually steered to a state with just a single cavity soliton. Bottom: spectrum of a single cavity soliton used in the experiments of Marin-Palomo and colleagues[6]. The smooth spectrum is favourable for experiments in fibre communications where individual spectral lines act as light sources for different wavelength-division multiplexed channels carrying data. Figure adapted from ref. 6, Macmillan Publishers Ltd.

an FSR of ~10 GHz and a quality factor that lies between those of whispering-gallery-mode and microring resonators.

The initial stage of Kerr comb generation is usually described in a four-wave mixing picture, in which the CW pump builds up to high intensity as it is tuned towards resonance and provides parametric gain, allowing the growth of new frequency components at other cavity resonances. With continued tuning, a cascade of non-degenerate four-wave mixing processes takes place, leading to a modulational instability regime, similar to that which takes place in the anomalous dispersion regime of optical fibres, in which intensity noise is amplified. The result in the time domain is a highly structured but noisy field that fills the microresonator (Fig. 2). On further tuning, the field transitions into the cavity soliton regime. Generally, the number of solitons generated is stochastic, but once generated the waveform is stable. The individual solitons correspond to femtosecond-scale ultrashort pulses with intensities far above that of the intracavity pump field. Now by tuning the pump backwards, it is possible to extinguish cavity solitons one by one, ultimately resulting in a single cavity soliton. At this stage, the comb spectrum is broad and smooth (Fig. 2).

The large spectral line density (many closely spaced comb lines) together with good optical signal-to-noise ratio and high stability of such Kerr combs is potentially highly attractive for dense wavelength-division multiplexing (WDM) optical communications. Usually in WDM, a single laser must be used for each separate wavelength communication channel; but Kerr combs offer the enticing prospect of replacing a large number of lasers with just a single CW pump and a microresonator.

Marin-Palomo *et al.* illustrate this promise very clearly[6]. In a first experiment, they use 94 comb lines spaced by 100 GHz with 40 Gbaud symbol rate and multiple bits per symbol to demonstrate 30 Tb s^{-1} transmission. In a second experiment, they interleave two similar 100 GHz Kerr combs to realize 179 carriers at 50 GHz spacing (roughly the minimum spacing needed to accommodate the data modulation) to achieve >50 Tb s^{-1} transmission. Although in principle such a comb should be achievable from a single microring, in practice this is challenging — partly because the pump power required is high and scales inversely with comb spacing. In a third experiment, the authors use one comb at the transmitter and a second, approximately matched comb as a multi-line local oscillator at the receiver, allowing parallel coherent detection. Similar to the comb at the transmitter, the comb at the receiver has the potential to replace a large array of lasers. In addition, the rigid frequency spacing of the comb offers a fundamental difference compared with arrays of lasers. By avoiding unknown drifts in the interchannel frequency spacing, a frequency comb enables more effective digital compensation of optical nonlinearities, the dominant factor limiting channel capacity in today's long-haul systems[10].

In contrast, Yang and colleagues' innovation is to drive a high-quality-factor whispering-gallery-mode resonator with two counter-propagating pumps at two different frequencies[7]. The offset in pump frequencies is controlled via a stable radiofrequency source using acousto-optic modulators. The authors find that they can generate counter-propagating cavity solitons and that under certain conditions, the combs can lock at a certain spectral line due to backscattering. Furthermore, they find that the counter-propagating solitons can be controlled to have a slight but highly stable difference in repetition rates (tens of kilohertz range). This situation is ideal for dual-comb spectroscopy, a powerful technique that exploits the beating of two slightly mismatched combs to convert the information in broadband optical spectra into an electrical format with a highly compressed bandwidth. Dual-comb spectroscopy using pairs of mode-locked laser combs has proved highly popular and can obviate the need for bulky spectrometers; similar techniques are also applicable to LIDAR and high-precision ranging[11]. Kerr combs offer the possibility for further miniaturization. Dual-comb spectroscopy using pairs of Kerr combs generated in two distinct resonators has recently been reported[12,13]; but Yang *et al.* are the first to demonstrate generation of a suitable comb pair from a single microresonator, which may offer the best prospects for stability.

Obrzud *et al.* also innovate in their pumping scheme, driving the cavity unidirectionally with a multi-frequency input[8]. The pump field is a comb that is externally generated via electro-optic (EO) modulation, consisting of about 20 lines with spacing carefully matched to the 9.77 GHz FSR of the cavity and compressed to yield pulses a few picoseconds in duration. Under appropriate conditions, a cavity soliton forms in the microcavity, comprising ~1,000 lines with an estimated pulse duration of ~140 fs. Previously, combs have been injected into FSR-matched resonant cavities to achieve intensity enhancement via coherent linear addition[14] and modulated CW inputs were used to drive nonlinear fibre cavities to induce or manipulate cavity solitons[15]. The present work differs in that the modulation of the pump field succeeds to steer the nonlinear soliton formation process despite the four order of magnitude faster round trip time compared with fibre loops. One impact is on efficiency: the conversion of pump power into the cavity soliton comb is estimated at 5%, a 5–10 times improvement compared with typical CW-pumped cases. This improvement stems from better overlap of the drive field with the short soliton pulse. Another advantage is that the cavity soliton is locked to the periodic drive field over a certain range of repetition rates; therefore, the soliton enjoys the inherent flexibility in repetition rate of EO comb sources. In this sense, the system may be seen as a hybrid of EO and microresonator comb generators, with EO techniques providing a repetition-rate-tunable seed and the microcavity providing efficient nonlinear spectral broadening at power levels substantially below what would be required for spectral broadening in single-pass nonlinear waveguides.

The cavity solitons discussed here exist in microresonators featuring anomalous dispersion (the situation where longer wavelengths propagate slower than shorter wavelengths) and are analogous to bright solitons that have been observed in anomalous dispersion optical fibres since the 1980s. In normal dispersion microresonators, mode-locked dark pulses have been observed[16], in loose analogy to dark solitons that can exist in normal dispersion fibres. Combs comprising mode-locked dark pulses have achieved efficiencies >30% but have not yet demonstrated optical bandwidths as large as those of bright cavity solitons and are in general less studied. At this point, clearly delineating the relative strengths and weaknesses of these two families of combs remains an open question.

Kerr combs, and in particular those based on cavity solitons, are approaching maturity and serious effort towards photonic integration is now required to encourage deployment of the technology. For true miniaturization, pump lasers providing adequate power and suitable linewidth should either be brought on chip or assembled in a compact package; however, chip-scale microring resonators still have relatively high pump-power requirements while whispering-gallery-mode resonators need continued progress in realization of robust coupling structures. For communication transmitter applications, Kerr combs would be more competitive if channel-by-channel modulators were available on chip, as they are for InP photonic integrated circuit transmitter chips featuring tunable laser arrays. Photonic integration should also provide additional opportunities for control of Kerr comb generation, in addition to the research already taking place on compound resonators, drop ports and thermal tuning. Ultimately, integration with electronic circuits will be desirable to realize truly portable and functional comb generator systems on a chip. ❐

Andrew M. Weiner is at the School of Electrical and Computer Engineering, Birck Nanotechnology Center, and Purdue Quantum Center at Purdue University, West Lafayette, Indiana 47907, USA.
e-mail: amw@purdue.edu

References

1. Ye, J. & Cundiff, S. T. (eds) *Femtosecond Optical Frequency Comb: Principle, Operation, and Applications* (Springer, 2005).
2. Del Haye, P. *et al. Nature* **450,** 1214–1217 (2007).
3. Ferdous, F. *et al. Nat. Photon.* **5,** 770–776 (2011).
4. Saha, K. *et al. Opt. Express* **21,** 1335–1343 (2013).
5. Herr, T. *et al. Nat. Photon.* **8,** 145–152 (2014).
6. Marin-Palomo, P. *et al. Nature* **546,** 274–279 (2017).
7. Yang, Q.-F., Yi, X., Yang, K. Y. & Vahala, K. *Nat. Photon.* **11,** 560–564 (2017).
8. Obrzud, E., Lecomte, S. & Herr, T. *Nat. Photon.* **11,** 600–607 (2017).
9. Lee, H. *et al. Nat. Photon.* **6,** 369–373 (2012).
10. Temprana, E. *et al. Science* **348,** 1445–1448 (2015).
11. Coddington, I., Swann, W., Nenadovic, L. & Newbury, N. *Nat. Photon.* **3,** 351–356 (2009).
12. Suh, M.-G., Yang, Q.-F., Yang, K. Y., Yi, X. & Vahala, K. J. *Science* **354,** 600–603 (2016).
13. Dutt, A. *et al.* Preprint at http://arXiv.org/abs/1611.07673 (2016).
14. Jones, R. J. & Ye, J. *Opt. Lett.* **27,** 1848–1850 (2002).
15. Leo, F. *et al. Nat. Photon.* **4,** 471–476 (2010).
16. Xue, X. *et al. Nat. Photon.* **9,** 594–600 (2015).

QUANTUM OPTICS

Nanotube chemistry tunes light

Room-temperature single-photon emission at several wavelengths in the near-infrared, including the telecom window, is realized by organic colour centres chemically implanted on chirality-defined single-walled carbon nanotubes.

Kartik Srinivasan and Ming Zheng

Single-photon sources (SPSs) — optical devices that emit one photon at a time — are an important resource for both fundamental and applied research in quantum science and technology[1]. While spontaneous parametric down-conversion in a nonlinear crystal has been a popular approach for realizing such sources, the intrinsic probabilistic nature of the emission process is a limitation. In contrast, sources based on an optical transition in an isolated quantum emitter — such as a neutral atom, trapped ion, semiconductor quantum dot, or colour centre in a crystal — can produce single photons ‘on demand’, so that each excitation pulse results in a single photon with near-unity probability.

Now, writing in *Nature Photonics*, Xiaowei He and colleagues report on-demand SPSs based on colour centre defects in single-walled carbon nanotubes (SWCNTs)[2]. Although SWCNTs have been investigated as potential SPSs since the first demonstration of photon antibunching in this system by Högele *et al.* in 2008[3], the sources of He *et al.* are distinguished by their room-temperature operation and emission in the telecommunications band, both of which are of direct relevance to applications, particularly in quantum communications.

A SWCNT can be considered as a graphene sheet rolled up along a lattice vector, denoted by indices (n, m), into a seamless cylinder. This leads to many chiral forms of SWCNTs whose atomic structures are uniquely determined by their (n, m) indices (Fig. 1), which effectively give the angle of the rolling with respect to the carbon lattice and the diameter of the resulting tube. A SWCNT can be either metallic (when $n - m = 3k$, where k is an integer) or semiconducting (when $n - m \neq 3k$); the bandgap of the latter is