One alternative is to use NV centres in high-quality bulk diamond by placing a thin film of diamond in an extremely high-Q external cavity to generate the required emission enhancements. Another alternative is to fabricate smaller mode volume cavities directly in the diamond. Faraon *et al.* take the latter approach by fabricating microrings directly in diamond[3]. These microrings are 4.8 μm in diameter, have radial thicknesses of 700 nm and are etched in 5-μm-thick diamond films that are subsequently thinned to 280 nm. The rings support whispering-gallery-style modes whose Q-factors are predominantly determined by scattering from the ring's side walls.

The NV centres form in the diamond during the growth process. These intrinsic NV centres are believed to show the most promise for technological exploitation because they exhibit longer spin lifetimes than either artificially created defect centres or defects in nanocrystals. In addition, they often possess transform-limited optical linewidths and, in the highest-quality chemical-vapour-deposited diamond, low-ensemble inhomogeneous broadening. Unfortunately, however, the strain generated by the microring fabrication process means that the NV centres investigated by Faraon *et al.* are not of the highest quality. This is not yet a cause for concern, particularly given the rapid progress in our ability to engineer the local environments of defect centres. We can therefore be optimistic that it will be possible to either minimize the induced strain at the initial processing stage or develop techniques that can be used to relax the strain at some later stage in the fabrication procedure.

Faraon *et al.* optically characterized their microrings by looking for couplings between the cavity modes and the NV emission lines. In order to tune the cavity modes through the NV centre emission frequencies, the cryogenic nature of the measurements was used to good effect: introducing xenon gas into the cryostat saw it condense on the microring, thus shifting the cavity modes while leaving the NV centres unaffected. A clear enhancement of the ZPL emission is seen when the NV centre is resonant with the cavity (Fig. 1c), which indicates a coupling between the defect and the cavity. Further evidence for this was obtained from time-resolved photoluminescence measurements, in which enhanced emission in the ZPL manifests as a decreased lifetime for the state (Fig. 1d).

One limitation of the technique is that there was no initial mapping of defect centres, meaning that the defect was not necessarily at a position in the microring that allows for optimal coupling to the cavity modes. We have recently shown how this could be overcome by registering photonic structures in diamond to individual NV centres[11]. ❐

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FREQUENCY COMBS

Liberated from material dispersion

A spheroidal shape of microresonator avoids the traditional wavelength limitations imposed by the resonator material in the generation of microresonator-based optical frequency combs.

Kjeld S. E. Eikema

It is difficult to overstate the impact that optical frequency combs have had in many fields of science and technology. The amazing properties of frequency combs come from the special relationship that exists between their spectrum, which comprises many equidistantly spaced discrete frequencies, and their seemingly pulsed output, caused by interference between these frequencies. Both aspects together give rise to unprecedented possibilities for achieving highly accurate control and measurement of time and frequency. The first demonstrations of optical frequency combs based on ultrafast mode-locked lasers[1–3] were made over ten years ago, and since then a myriad of applications have emerged[4]. These include ultraprecise optical atomic clocks with accuracies approaching 18 decimal places[5], precision spectroscopy and investigations into the constancy of fundamental constants[6,7], rapid broadband and sensitive spectroscopy[8], long-distance measurement[9] and optical arbitrary waveform generation[10]. Combs have even helped the emergence of new fields such as attosecond science[11].

Most optical frequency comb implementations in use today are still based on near-infrared mode-locked lasers. Although these systems can easily produce up to a million frequency-comb 'teeth' (modes) covering most of the visible and infrared spectrum, they are relatively large (about 1 m) and expensive. An important step towards the miniaturization and possible integration of frequency combs with fibre optics was made in 2007 with the first demonstration of a comb-like spectrum using microresonators[12]. One year later, full frequency comb operation was demonstrated near a wavelength of 1,570 nm using a resonator only 0.75 mm in size[13]. This remarkable achievement has opened vistas towards fully integrated, low-cost frequency combs. However, the dispersion properties of microresonators used so far have limited comb generation in these devices to wavelengths larger than 1,000 nm.

Reporting in *Nature Photonics*, a group of researchers led by Luke Maleki have now shown that a new shape of resonator may avoid this wavelength limitation[14]. They demonstrate a comb-like spectrum near 800 nm from a CaF_2 resonator, despite the unfavourable dispersion properties of this material at this wavelength. The method should in principle be applicable to even shorter wavelengths, allowing future microresonator frequency combs to cover the entire visible spectral range, similar to their counterparts based on mode-locked lasers.

Two properties form the basis of a frequency comb. First, its (optical) spectrum should comprise exactly regularly spaced frequencies such that it can be described by an offset frequency f_{ceo}, the spacing between the frequencies f_{rep}, and an index indicating the position (mode number n) in the comb spectrum. Second, each of these frequencies must have a fixed phase relation to all other frequencies. If this is the case, then the optical waves of all comb frequencies will interfere to form what looks like a repetitive (but possibly complex) pulse train. The repetition frequency of this pulse train is equal to the frequency spacing f_{rep} between adjacent modes. Similarly, the phase evolution between subsequent pulses is directly related to the offset frequency f_{ceo} of the comb spectrum. This means that the comb spectrum and the pulses that result from the interference can be controlled through just two variables — f_{rep} and f_{ceo}. Both are typically in the radiofrequency domain of 100–1,000 MHz for laser-based systems, and can be measured electronically with high precision by comparison with a frequency standard such as an atomic clock. Once this is done, all the optical comb frequencies are known to a similar precision, and thus the phase evolution of the pulse train is known with subwavelength resolution. This has enabled the study of, for example, electron dynamics at attosecond timescales[11].

Frequency combs based on microresonators can be applied in a similar way as those based on lasers, but there are some significant differences in their properties and mode of operation. The small size of a microresonator, which is typically toroidal in shape and has a diameter of less than 1 mm, results in a comb spectrum that has large mode spacings (many tens of gigahertz). Although this is useful for applications such as the calibration of astronomical spectra, for many other applications it is quite high. Furthermore, there is no active lasing medium; rather, the generation of the comb modes relies entirely on strong nonlinear optical interactions by light travelling in the resonator. For this reason it is useful that the light is confined to a small space and that microcavities are produced with very low optical losses.

Inside a resonator, light can circulate for many thousands of cycles in what are known as 'whispering gallery modes'. Comb generation is initiated by light from a continuous and fixed-frequency 'pump' laser that is coupled to the resonator using evanescent waves. Light accumulates inside the resonator with little loss, allowing very high intensities to be achieved even at milliwatt pump powers. The initial response of the resonator is to create two sidebands symmetrically around the pump laser frequency. If the pump light is strong enough, a cascade of nonlinear interactions — non-degenerate four-wave mixing — is set in motion, creating many new frequencies with the same spacing. The resulting comb is often known as a 'Kerr-comb' because of its nonlinear origin. There are some complications, however, because the group-velocity dispersion, which includes both material and geometrical dispersions, displaces the modes of the resonator from equal-frequency spacing. Under the right conditions, which are a slightly negative (or 'anomalous') group-velocity dispersion in the wavelength region of interest and high enough intensity in the resonator, nonlinear effects pull the modes to the right positions. This allows the generation of broadband frequency combs over hundreds of nanometres near a central wavelength of 1,550 nm. However, at wavelengths below 1,000 nm, the positive (or 'normal') group-velocity dispersion in microtoroidal resonators has previously been too strong for comb generation to succeed.

The technique of Maleki and co-workers is a clever way around this limitation[14]. The key is that their resonator is not toroidal, but is instead based on a truncated spheroid of crystalline CaF_2. A spheroidal resonator exhibits transverse (vertical) modes in addition to the azimuthal modes observable in toroidal resonators. These vertical modes have enough anomalous geometrical dispersion to compensate for the material dispersion of the resonator material, which allows a comb-like spectrum to be generated in microresonators near a wavelength of 794 nm. This central wavelength can in principle be tuned over the transparency range of the material by changing the resonator geometry and pump wavelength. The work of Maleki and co-workers therefore essentially liberates microresonator-based frequency comb generation from the dispersion properties of the resonator material.

The geometry of the resonator also affects the mode spacing in an interesting way. The vertical mode spacing is often significantly larger or smaller than that of the azimuthal modes, depending on the ratio between the small and large semi-axes of the spheroid. Maleki and co-workers expected an azimuthal mode spacing of 8 GHz for their oblate spheroid, and predicted the vertical mode spacing should be three times larger than this value. The team experimentally observed a vertical mode spacing very close to 24 GHz, proving that vertical cavity modes are indeed at work. The dependence of the vertical mode

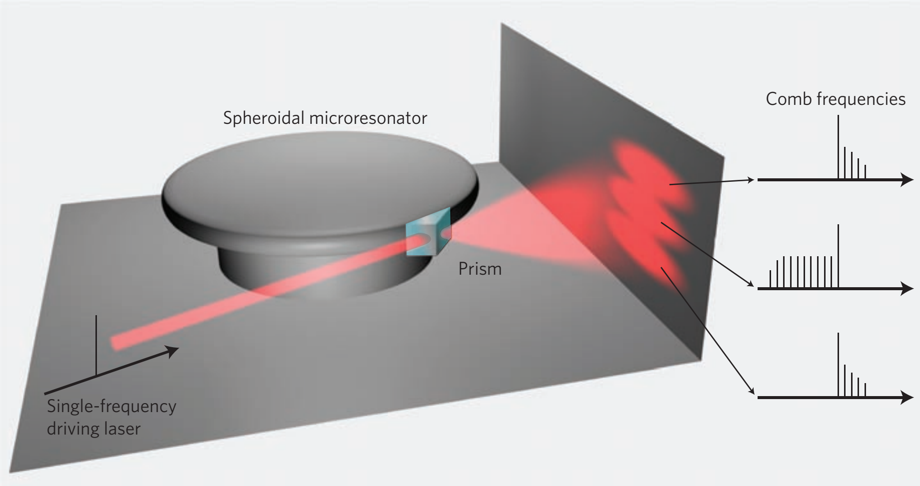

Figure 1 | Microresonators can confine light to a small volume for long periods of time. If a continuous-wave, single-frequency driving laser (a 'pump') is coupled to such a resonator, its intensity can be enhanced to a level at which the response of the resonator material becomes highly nonlinear. Maleki and co-workers[14] use this effect in a CaF_2 spheroidal microcavity to convert a single-frequency laser into a comb of frequencies. By using transversal (vertical) modes of the resonator, the researchers were able to generate a comb at a wavelength of 794 nm, where material dispersion normally prevents this process. In this mode of operation, comb frequencies below that of the driving laser are emitted close to the resonator plane, whereas higher frequencies are emitted away from the plane.

spacing on the resonator geometry will allow a much wider range of mode spacings than is possible by simply changing the resonator size. The researchers speculate that a mode spacing as low as 1 MHz might be feasible for a nearly spherical resonator of only 0.1 mm diameter, which is currently unattainable for toroidal microresonators.

Frequency comb generation in spheroidal resonators does, however, come at a price. The comb spectrum near 794 nm seems to be only a few nanometres wide. This is partly because of the limited number of participating vertical modes, but also because of their spatial separation both inside and outside the resonator. Higher-order vertical modes (at higher frequencies) are emitted away from the plane of the resonator, in contrast with the azimuthal modes used in toroidal resonators. If the output coupler is placed in the plane of the resonator, as shown in Fig. 1, only low-order comb vertical modes are collected, leading to the highly asymmetric comb spectrum observed by Maleki and co-workers. As expected, higher-order modes were observed by moving the output coupler out of the plane.

The coherence and spacing of the vertical modes still need to be verified before this system can fully qualify as a frequency comb. A demonstration of referencing the modes to a frequency standard is also required. Self-referencing to measure f_{ceo} will probably be quite difficult, as this requires an octave-wide comb spectrum. However, for less demanding applications, one could also reference the comb to an atomic or molecular transition.

The biggest challenge ahead will probably be to broaden the combs from spheroidal resonators, as many applications require a spectrum that is much wider than a few nanometres. This is especially true for applications that would benefit from the multigigahertz mode spacing of these combs, such as optical sensing or the calibration of astrophysical spectra ('astrocombs'). Broadening the available spectrum could be achieved by improving light collection from the resonator, or perhaps through the use of multiple resonators.

If such spectral broadening is successful, microresonator-based combs could replace many current laser-based systems, with far-reaching benefits. This work also demonstrates once again that frequency combs are becoming ever more universal. It would therefore not be surprising if, in ten years time, they are as widespread and relied upon as computers. ❐

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