of excitons trapped within a confining potential[7]. Nevertheless, it may prove difficult to apply excitonic devices to systems that rely on wavelength-division multiplexing, where such a wavelength shift may move the photon out of the desired communication channel.

Excitonic switches are a new and relatively unexplored technology. However, in the competition to bridge electronics and optics, the team at UCSD and UCSB has demonstrated that excitons possess at least two compelling advantages: excitons are tiny (comparable in size to electrons), and exciton current can be directly modulated using an external potential. Perhaps there is an alternative to wires after all. ❐

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LIQUID CRYSTALS

Tunable whispers

The news that spherical droplets of a liquid crystal can function as whispering-gallery-mode microresonators with an unprecedented width of wavelength tunability could be good news for fabricating new kinds of sensors and lasers.

Hiroshi Yokoyama

In New York's Grand Central Station, close to the Oyster Bar & Restaurant, is the famous 'whispering gallery' where people can talk across the wide corridor as if they are standing next to each other. The scheme works because the acoustic waves of the speaker's voice are reflected along the large arched ceiling and sent to a listener with little attenuation — a counterintuitive and striking sensation. The same principle, albeit at only a millionth of the scale, applies to optical waves and has made high-performance optical microresonators possible for the past two decades[1].

Just a few tens of micrometres in diameter, optical whispering-gallery-mode (WGM) microresonators are typically made from dielectric spheres or discs, and feature optical waves that circulate along their periphery by total internal reflection. The resonance occurs for an optical wave when the round-trip phase of one circulation is an integral multiple of 2π. The attraction of WGM microresonators is their extremely high *Q*-factors[2] (determined by the sharpness of the resonance spectrum; peak wavelength divided by spectral width), which can reach as high as 10^{10}. A secondary benefit is the small volume of the resonators compared with their bulky linear-cavity counterparts. The higher the *Q*-factor, the longer the photons survive inside the resonator and the stronger the light–matter coupling. This feature makes WGM microresonators ideal for studying fundamental quantum physics[3] and useful for creating low-threshold lasers, efficient optical components and sensors[4].

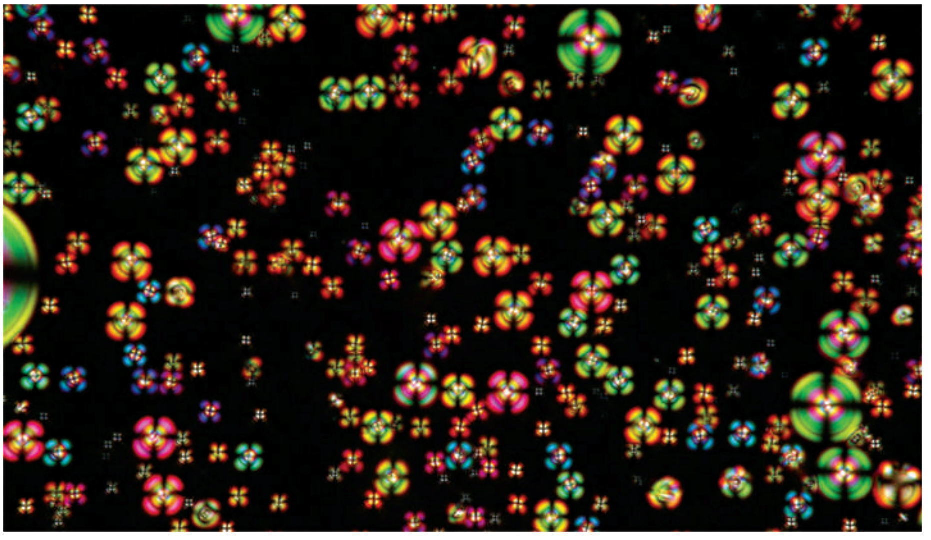

Figure 1 | Spherical nematic liquid-crystal droplets in a polymer matrix as observed under a polarizing microscope with crossed polarizers.

Conventional WGM microresonators are made of transparent solids such as silica glass. One drawback is that because the resonance wavelength is determined by the shape and size of the microresonator, it is difficult to tune. For many practical and even scientific applications, however, it is desirable to be able to continuously vary the resonance wavelength as widely, precisely and quickly as possible. Although there have been numerous attempts to realize tunable WGM microresonators by a variety of means[1,3], the tuning range achieved is often too small or response time too slow for practical applications. On page 595 of this issue[5], the group led by Igor Muševič from the Jožef Stefan Institute and the University of Ljubljana, Slovenia, describe a new design of spherical WGM microresonator that has unprecedented electrical tunability of 20 nm for an electric field strength of 2.6 V μm^{-1} — approximately two orders of magnitude larger than that achieved in solid-state microresonators.

The sphere is made of a nematic liquid crystal dispersed in an optically transparent rubber, polydimethylsiloxane (PDMS). The nematic liquid crystal is essentially the same as that used in liquid-crystal display TVs — an ordered liquid with uniaxial optical anisotropy due to the spontaneous orientation of constituent rod-like molecules.

The fabrication process is simple; a mixture of a small amount of liquid crystal and the rubber precursor is mechanically stirred to form liquid-crystal droplets in the desired size range. The droplet quickly adopts a spherical shape by surface tension and is gently fixed as the crosslinking in the PDMS proceeds. This type of polymer–liquid-crystal composite, referred to as a polymer-dispersed liquid crystal (PDLC), has been in existence for over 20 years and is commercially available as a 'smart window', which can electrically switch between clear and opaque states[6].

Unlike most PDLC applications where the liquid-crystal droplets are kept small for intense light scattering, Muševič and co-workers use larger spherical droplets with diameters upwards of 10 μm (Fig. 1) to serve as optical microresonators. Inside the sphere, the liquid-crystal molecules are forced to radially orient themselves by the perpendicular anchoring condition at the liquid-crystal–PDMS interface, indicated by dark solid lines in Fig. 2a. The optical wave travels along the meridian of the sphere. An interesting feature of the lowest-order eigenmode (Fig. 2a) is that the light is linearly polarized with the electric field vector oscillating in the radial direction, parallel to the liquid-crystal orientation. This is because the liquid crystal has the highest refractive index (extraordinary index n_e) for such a polarization, thereby making it easier to meet the condition of total internal reflection. When the polarization is such that the electric field vector is perpendicular to the radial axis, the relevant refractive index is now the ordinary index n_o, which is typically 0.1–0.3 less than n_e, and hence total internal reflection becomes increasingly more difficult in smaller droplets. This large optical anisotropy is the basis of all known unique electro–optical functionalities of liquid crystals, and it is also true in this liquid-crystal WGM microresonator.

The tunability of the WGM resonance comes from the electric-field-induced reorientation of the liquid-crystal optical axis inside the droplet. Shown in Fig. 2b is the liquid-crystal configuration attained under an intense electric field; the liquid crystal is aligned completely parallel to the vertically applied electric field. Because the optical wave's electric field vector travelling along the meridian can no longer always be parallel to the liquid-crystal orientation, it feels a somewhat reduced refractive index, and hence the resonance condition is pushed towards a shorter wavelength. Muševič and co-workers show that a 20 nm shift in resonance wavelength is possible even at a fairly weak electric field of 2.6 V μm^{-1} within 10 ms or so. As the separation between neighbouring resonance peaks is less than 10 nm for a droplet with diameter larger than 10 μm, this tunability is actually large enough to cover the entire spectrum of visible light, as long as the liquid crystal remains transparent.

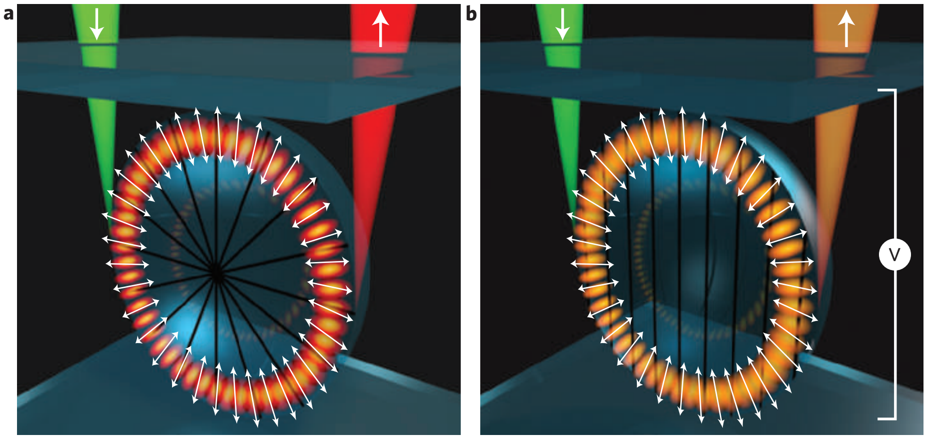

Figure 2 | Cross-sectional view of the whispering-gallery-mode microresonator formed from a nematic liquid-crystal droplet. **a**, Initial state without an electric field. The liquid-crystal orientation (dark solid lines) is radial with a point defect at the centre. **b**, Liquid-crystal orientation (dark solid lines) under a strong electric field that is misaligned with the optical electric vector (white arrows), resulting in a shift in resonance towards shorter wavelengths.

Nematic liquid crystals are in fact opaque liquids in bulk states. They do not actually absorb visible light, however, the opacity is due to the scattering of light by spatial variations of their orientation, dynamically induced by thermal fluctuations. Because these fluctuations are so strong, thermal light-scattering is always a concern when liquid crystals are to be applied to low-loss sophisticated photonic devices. For the WGM microresonator, the scattering loss would adversely affect the *Q*-factor. Fortunately, however, Muševič and co-workers show that the *Q*-factor can be reasonably high, up to 12,000. This value is orders of magnitude lower than silica-based WGM microresonators, yet comparable to that of the recently developed surface-plasmon WGM microresonator[2], and may be large enough to allow a variety of applications, including mirror-less lasers. Indeed, other types of liquid crystals with indigenous photonic crystal structures — cholesteric[7] and blue[8] phases — have been demonstrated to constitute a self-organized mirror-less laser with an extremely low threshold, despite the existence of an equal level of thermal light-scattering.

An important caveat to add finally is that it is not yet clear where the light loss actually originates from in the liquid-crystal-based WGM microresonator. The observation that the *Q*-factor significantly improves in larger droplets suggests that thermal light-scattering is not a major source of loss. The roughness of the liquid-crystal–PDMS interface and deviation from the spherical shape may perhaps have a role. Owing to the crude fabrication process used, it is possible that the theoretical limit of the *Q*-factor could in fact be much higher than that attained at present. Thermal fluctuations not only scatter light, but also dynamically modify the mode profile in such a way as to intrinsically shift the resonance frequency, yielding apparently wider resonance spectra. This is not at all bad news; as the fluctuation–dissipation theorem indicates, a more significant role of fluctuations means a higher sensitivity to external stimuli, here affecting the boundary orientation of the liquid crystal. Ultimately, the unique softness of the liquid-crystal-based WGM microresonator could make a promising environmental or biochemical sensor device that is small, easy to make and highly sensitive. ❐

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