QUANTUM OPTICS

Boosting photon storage

Controlling light confinement inside microcavities is crucial to the development of optoelectronic devices such as miniaturized semiconductor lasers. A welcome step in this direction is the successful design of a toroid-shaped microresonator able to trap photons with unprecedented efficiency.

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Much like the body of a wind instrument, a resonant cavity is one in which standing waves (of acoustic or electromagnetic origin) can build up. In such resonators, there is a discrete spectrum of allowed standing waves, corresponding to acoustic notes or 'resonant modes'. Optical microcavities are resonators able to confine light in one or more dimensions on the scale of its optical wavelength. These structures are commonly used to tailor the optical properties of materials inserted inside them, including spontaneous emission. Whether useful or detrimental, spontaneous emission plays a key role in many opto-electronic devices. For example, in semiconductor lasers, spontaneous emission into the so-called lasing mode is essential, because it provides photons that are subsequently amplified by stimulated emission. By contrast, spontaneous emission into other non-lasing modes is detrimental, because it tends to increase the threshold current required to initiate lasing. Armani and colleagues[1] present in *Nature* a novel chip-based optical resonator (Fig. 1a), which could reduce by several orders of magnitude the minimum threshold current of semi-conductor lasers.

The inhibition and enhancement of spontaneous emission by microcavities was first demonstrated in a beautiful series of experiments on atoms in the early 1980s[2], which led to, among other things, single-atom lasing[3]. These experiments, conducted at the interface between quantum optics and atomic physics, gave birth to the field of cavity quantum electrodynamics (CQED). Since the 1990s, several conceptual and technological breakthroughs have led to the development of solid-state optical microcavities able to support discrete resonant modes, confined in all three dimensions, which opened the way to applications of CQED in optoelectronics[4]. For example, silica microspheres are able to trap photons for a very long time ($\tau \sim 1$ µs) by total internal reflection, which results in resonant modes with very high-cavity 'Q factors' (for a given wavelength, Q is proportional to τ). This makes them particularly well suited to low-threshold lasing[5].

By contrast, the resonant modes of semiconductor microcavities — such as micropillars, microdisks and cavities based on photonic crystals — have much lower Q factors, limited by optical scattering induced by the roughness of their sidewalls. Nonetheless, they do have extremely small cavity volumes, V, which allows them to enhance the spontaneous emission of quasi-monochromatic emitters using the so-called Purcell effect (which scales as Q/V). This effect has been observed in microdisk[6] and micropillar[7] cavities, by using self-assembled quantum dots as artificial atoms (Fig. 1b,c). The Purcell effect can be used to funnel the spontaneous emission into a single resonant mode, which is essential for developing solid-state sources of single photons[7,8,9] — the only existing device to actually use CQED.

Nonetheless, many important CQED effects have not yet been observed for a discrete solid-state emitter, including reversible spontaneous emission in the so-called strong coupling regime. The development of high-Q toroid microcavities by Armani and colleagues[1] changes all this (Fig. 1a). These microcavities, which are created from a silica microdisk by melting and reshaping its edges with a laser, combine the best of both approaches. As with microspheres, the surface tension of molten silica leads to an excellent surface smoothness and thus to a ~10,000-fold improvement of their Q factor when compared to microdisks. But like microdisks, the microfabrication process ensures excellent control of the cavity size and position on the chip, allowing potential integration with other optical components such as waveguides. Moreover, the diameter of the microtoroids can potentially be scaled down to 10 µm from their present 100 µm, so their cavity volume V

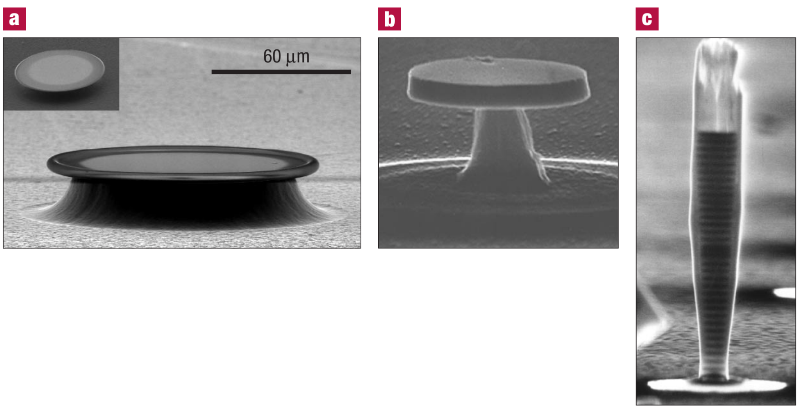

Figure 1 Microcavity resonators of varying shapes and sizes. **a**, The toroid-shaped resonators created by Armani *et al.*[1] are 100 µm across (cavity volume, $V \sim 1{,}000\,(\lambda/n)^3$, where λ is the optical wavelength and n the refractive index of the material) and they can store photons for a long time (corresponding to a high-cavity Q factor of 1×10^8). **b**, A 2-µm diameter microdisk, with Q and V values of 12,000 and 6 $(\lambda/n)^3$, respectively. **c**, A 1-µm diameter micropillar, with Q and V values of 2,000 and 5 $(\lambda/n)^3$, respectively. (Figs 1b and 1c courtesy of CNRS/LPN, France.)

would then become comparable, within a factor of 10, to microdisks or micropillars.

This unique combination of properties opens several promising avenues for solid-state CQED. For example, in microcavity lasers, the lasing threshold is reached when, on average, one photon occupies the resonant mode. The extremely long photon trapping times (~40 ns) observed by Armani *et al.* for toroid microcavities is especially attractive for developing very low threshold lasers. As with microspheres[5], doping silica toroids with rare-earth ions could lead to optically pumped lasers with a sub-microwatt lasing threshold. Provided this can be done on a semiconductor substrate, such as GaAs, toroid microcavities could also be used to build a fully integrated electrically pumped laser by coupling the resonator to a nearby semiconductor emitter, such as a collection of quantum dots. Simple estimates show that lasing could be achieved at room temperature with a much smaller threshold current (perhaps only 10 nA) than that achieved[10] by the best vertical-cavity surface emitting lasers (30 μA). Such sources would be very interesting for remote optical sensing, especially in an environmental or biomedical context. Low-threshold lasing and non-linear effects could also revive studies into optical computers, which were halted because the power required to operate elementary logic gates could not be scaled down.

At a more fundamental level, single quantum-dot lasing is now also within reach, provided temperatures typically lower than 50 K are used (at higher temperatures the quantum dot emission broadens spectrally, which reduces its coupling to the mode). Such a laser could display an even lower threshold current, in the picoampere range[11], together with other unusual effects, such as self-quenching and blinking. At temperatures as low as a few kelvin, single quantum dots could enter into a strong coupling regime, in which the emitted photon is trapped for such a long time in the cavity that it can be reabsorbed and reemitted by the quantum dot. Thanks to their small *V*, semiconductor microcavities[12] and microspheres, coupled to quantum dots, are close to demonstrating the strong-coupling regime, although they have various problems to overcome. Small toroidal microcavities in the 10 μm diameter range would represent a much better compromise between *Q* and *V* figures of merit to address this issue. Observing a strong coupling regime for single quantum dots would be a significant breakthrough in the field of quantum information processing. For example, potential quantum computers using quantum dots as qubits could use resonant coupling to a cavity mode to mediate interactions between distant quantum dots, and realize the two-qubit gates necessary for their operation[13].

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SHAPE-MEMORY ALLOYS

Combinatorial high jinks

A new strategy for mapping the mechanical and magnetic properties of thin films has been used to discover ferromagnetic shape-memory alloys with previously unknown compositions. The results provide new insight into an underlying composition–structure–property relationship of the Ni–Mn–Ga system.

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Combinatorial materials science[1] — the systematic study of material properties as a function of composition — was first introduced systematically in the search for new pharmaceutical drugs. Since 1995, it has also been applied successfully to a range of functional materials, with luminescent, superconducting or dielectric properties[2]. Usually, many small samples, differing slightly in composition, are deposited by an automatic computer-controlled method and then characterized, again by an automated method. (An alternative name for this approach is 'high-throughput screening'.) For screening of physical properties and to determine ternary phase diagrams, thin films deposited by sputtering in ultra-pure argon are generally preferred. Mechanical properties have also been studied,