MICROPHOTONICS

Toroid of many colours

A demonstration of continuous sum-frequency generation of visible light in a microscopic silica resonator could provide a light source for on-chip silicon photonics and applications in the UV.

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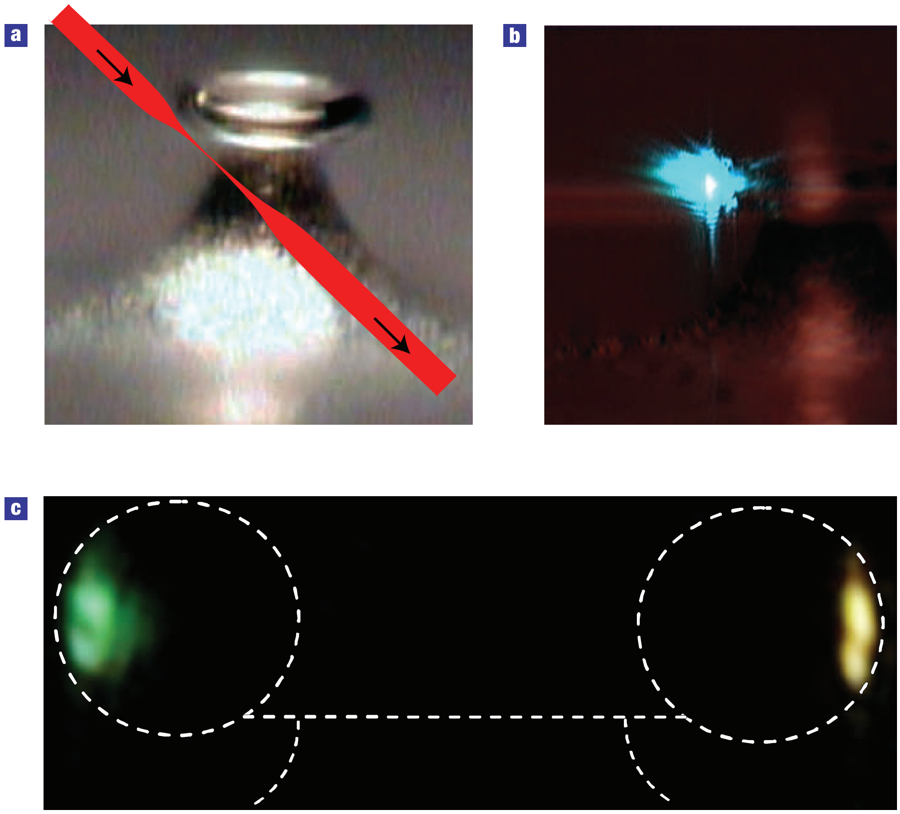

Figure 1 Third harmonic generation from a microtoroid. **a**, Photograph of the silica microtoroid structure used by Carmon and Vahala[2] along with the tapered fibre shown schematically (red). **b**, Blue emission from infrared pumping of the microtoroid, where the microtoroid is still dimly visible. **c**, Green and yellow emission generated with two different-wavelength counter-rotating pump lasers. (Images reproduced from ref. 2).

The ability to confine laser light within the small volumes of the so-called whispering gallery modes of high-Q-factor microdroplets and microspheres has led to the observation of a variety of remarkable nonlinear optical phenomena. One of the earliest examples of this was demonstrated in a study by Qian and Chang[1] into the effects of optical confinement on stimulated Raman scattering (SRS) in a 70-μm-diameter liquid droplet of carbon tetrachloride. The SRS shifts the wavelength of a small proportion of the light passing through a sample by a discrete amount determined by the chemical makeup of the sample. If the carbon tetrachloride were in the form of a bulk liquid instead of a microdroplet, generation of comparable amounts of SRS shifted multiple times would require many thousands larger volumes of liquid, with at least one linear dimension of metres. On page 430 of this issue, Carmon and Vahala use similar resonant-enhancement effects to shift light from infrared to visible wavelengths by a process of third harmonic (TH) generation in a 29-μm-diameter toroidal microcavity grown on a silicon chip[2]. Moreover, they do so with an unprecedented input-pump power of only 300 μW.

Third harmonic generation is a special instance of a more general class of optical processes known as sum-frequency (SF) generation, which involves the combination of multiple photons to produce a single photon of equivalent total energy. In simple terms, TH generation requires three photons to be in the same place at the same time. This means that although TH light is relatively easy to generate with very short, intense pump pulses, it is profoundly more difficult to do so with continuous light of the same average power. Moreover, because TH generation additionally requires that the input light wave has the same phase as the output light wave, and therefore requires both to be coherent, it is even more difficult to achieve than nonlinear optical processes that do not require phase matching. Consequently, despite the fact that a variety of nonlinear optical processes have now been observed in microdroplets under continuous illumination[3], as has TH generation using high-intensity pulses of the order of femtoseconds[4], TH and high-SF processes are rarely observed at pulse lengths longer than a nanosecond[5]. And certainly, even it if were possible to achieve TH generation with longer pulse lengths, the idea that it could be done at just 300 μW seems implausible by comparison. So how do Carmon and Vahala do it?

The answer lies in recent advances made in two principle areas. The first is in the technical ability to make micrometre-size resonant cavities, beginning with those used in microdisc (or ‘thumbtack’) lasers and leading to the sorts of toroidal silica resonators used by Carmon and Vahala, which can be precisely engineered to accommodate specific modes with well-defined resonant frequencies and modal field patterns. Compared with the microdroplets of earlier studies, toroidal cavities support fewer resonant modes, with less dispersion between mode frequencies[6] and more controlled modal volumes.

The second is in improvements in our ability to inject light into these cavities. This began with a demonstration[7] that light from a fibre whose cladding has been partially removed can be more efficiently coupled into specific modes of a resonant microsphere than by simply illuminating it with a plane wave or gaussian beam from a laser propagating in free space. This was subsequently improved on by Knight *et al.*[8] who achieved up to 90% coupling efficiency using a tapered fibre, and then ultimately by Vahala's group, who reached 99.97% coupling efficiency into a specific high-Q mode of a microtoroid[9].This approach not only provides near-perfect coupling efficiency, but by engineering the toroidal and tapered fibre together enables greater control over mode volume, mode dispersion and phase matching. Although the versatility of this approach had previously been used by Kippenberg *et al.*[6] to demonstrate continuous optical parametric oscillation, another process that requires phase matching of the input and output waves, the present paper[2] also illustrates how to design fibre–resonator combinations to match phases exactly.

That Carmon and Vahala demonstrate TH generation with a microresonator that is compatible with conventional CMOS technology, and might therefore be monolithically integrated with other electronic and photonic devices, is another potentially promising aspect of their work. Practical chip-fabrication issues may require replacing the tapered fibres with on-chip waveguides that couple to optical fibres at the edge of the chip. It is not immediately obvious that the SF shifts they demonstrate would have much use in applications such as all-optical routing, which require frequency shifts of the order of gigahertz. Moreover, the sensitivity of such a process to changes in temperature and other factors could be difficult to adapt to the demands of commercial telecommunications, which require stability over a wide temperature range, typically –20 to 30 °C. For other applications this extreme sensitivity can be turned into an important asset. For example, shifts in the resonant frequencies of chemically functionalized microspheres have already been used to detect extremely low concentrations of DNA in solution[10].

The demand for a versatile and compact UV light source for applications including optical data storage, spectroscopy, and environmental monitoring has driven substantial and continuing investment in the development of UV LEDs and diode lasers. Carmon and Vahala point out that with the recent demonstration of a high-Q microcavity made from CaF_2 (ref. 11), a material that is optically transparent down to wavelengths of around 190 nm, it should be possible to realize a UV light source based on the TH generation using more mature infrared and visible diode laser technology. This in turn would represent the ability to generate light over a substantial range of wavelengths, from the infrared to the UV, in pulses or continuously, by combining the light from a handful of pump-laser wavelengths.

References

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