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. ❐

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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

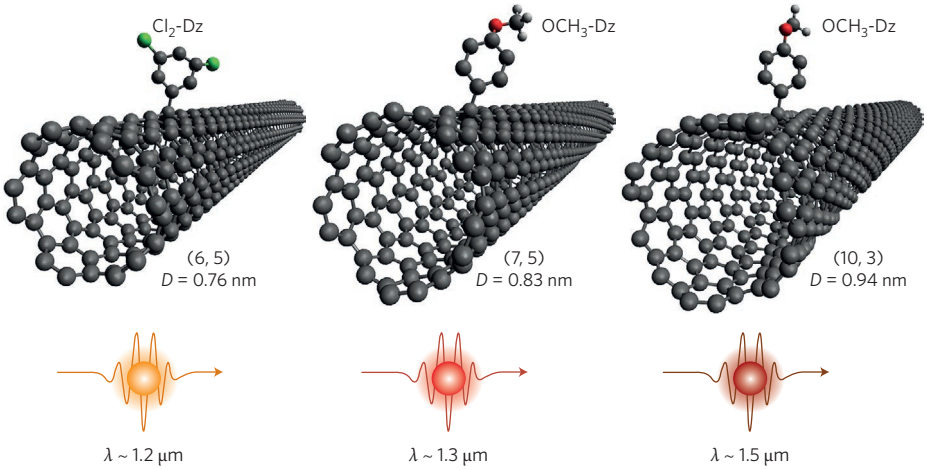

Figure 1 | Single-walled carbon nanotubes have many different structural forms as denoted by their (*n*, *m*) indices. By chemically functionalizing them with suitable organic molecules (3,5-dichlorobenzenediazonium (Cl_2-Dz) or 4-methoxybenzenediazonium (OCH_3-Dz)), colour centres that produce single-photon emission at various wavelengths can be realized. *D*, SWCNT diameter. Figure adapted from ref. 2, Macmillan Publishers Ltd.

proportional to the inverse of the tube diameter due to quantum confinement along the tube circumference. High-temperature gas-phase synthesis almost always produces a mixture of SWCNT species, but advances in post-synthesis sorting have nevertheless made many pure-chirality SWCNTs available, providing a material foundation for light-emission control[4]. Just like sp^2-carbon-based organic dye molecules, a semiconducting SWCNT fluoresces in the near-infrared region 800–2,500 nm, corresponding to its bandgap. The emitted light originates from multiple mobile excitons that coexist along the tube.

With all its atoms on the surface, chemical modification of a carbon nanotube — and, consequently, its photon emission — seems highly plausible. Indeed, Weisman and co-workers found in 2010 that by reacting SWCNTs with ozone, an oxygen colour centre is created whose emission is 100–200 meV redshifted from that of the mobile excitons of a pristine SWCNT[5]. In 2013, Wang and co-workers took a big step forward when they created sp^3-carbon-based organic colour centres by reacting SWCNTs with a series of aryl diazonium compounds, demonstrating a broader range of emission tunability[6]. Even though higher fluorescence quantum yields were observed in both the oxygen and the sp^3-carbon colour centres, suggesting exciton localization, photon correlation statistics from these emitters were not measured. However, the antibunching behaviour characteristic of single-photon emission (SPE) has been documented from SWCNTs at cryogenic temperatures[3]. One possible cause for this observation is exciton localization by shallow traps that are inadvertently introduced, suggesting that purposely implanted defects may create deeper traps that also give rise to SPE. Definitive confirmation came in 2015 when Doorn, Htoon and colleagues reported that SPE can indeed be observed from the oxygen colour centres even at room temperature, albeit with limited single-photon purity and emission stability[7].

The next logical step is the realization of SPE from SWCNT-based organic colour centres that is both tunable in wavelength and of higher quality. This is exactly what He *et al.* accomplished. Using three chiral forms of SWCNT to react with different aryl diazonium compounds, they created aryl-based organic colour centres that emit at wavelengths from 1.1 μm to 1.55 μm (Fig. 1), covering the telecom O- and C-bands. The molecular tunability of their approach is essential to create strongly localized excitons and high-quality SPE across a broad spectral range. The single-photon purity from these organic colour centres is as high as 99%, approaching that of the best SPSs. The majority of all the investigated nanotubes showed more than a tenfold reduction in unwanted multiphoton emission compared with SPE, even when the nanotubes were driven towards saturation. Moreover, the observed SPE occurs at room temperature, with much improved stability and brightness (100 kHz count rate) compared with oxygen colour centres. These characteristics, in combination with the promising possibilities of electrically driven emission[8], coupling to photonic cavities[9] and controlled nanotube assembly, suggest enormous potential for SWCNT-hosted organic colour centres in quantum information technology. Such sources already compare favourably with other systems that have exhibited room-temperature SPE, including colour centres in diamond, single molecules in organic crystals, defects in wide-bandgap semiconductors and colloidal quantum dots[10].

Given the progress reported by He *et al.*, it is natural to ask if SWCNT-hosted organic colour centres are now the most promising material system for single-photon generation. As might be expected, an answer to this question depends on the intended application. Along with brightness (flux of usable single photons) and purity (degree to which multiphoton emission is suppressed), some quantum applications need photons that are indistinguishable — that is, have identical spectro-temporal wavepackets. Such indistinguishability, yet to be demonstrated for SWCNT sources, enables quantum interference of photons, which is at the heart of generating entanglement for use in applications such as quantum simulation, for example.

A remaining challenge is the development of a SPS that simultaneously delivers all of the above characteristics with a high level of performance. Self-assembled InAs/GaAs quantum dots, operating at wavelengths near 900 nm and temperatures below 10 K, currently exhibit the highest performance of any SPS based on a single quantum emitter. The road from the first demonstration of this system nearly two decades ago[11] to recent works reporting simultaneously bright, pure and indistinguishable SPE[12–14] has required many advances in fabrication, spectroscopy and conceptual understanding of the physical mechanisms underpinning non-ideal behaviour. On the other hand, emission at the desirable telecom window of 1,550 nm remains challenging, although the use of other epitaxial materials (for example, InAs/InP; ref. 15) or nonlinear optics to spectrally translate an already-developed source into the desired wavelength range[16] are both feasible. Still, room-temperature operation appears to be out of reach, and variability in the quantum dot emission wavelength due to sample inhomogeneity potentially hampers the scaling-up of the approach.

Whereas the optical dipole created by an InAs/GaAs quantum dot is due to the contribution of many thousands of atoms, whose precise number and arrangement potentially varies from one quantum dot to another, organic colour centres in SWCNTs can in principle consist of a single, chemically controlled defect with well-defined molecular configuration. Going forward, it thus seems that there is significant scope to engineer the quality and uniformity of these sources. For example, the work of He *et al.* shows significant emission inhomogeneity: for a given nanotube and chemical functionalization, the authors found that SPE can occur at a few different wavelengths. This variation is presumably due to the multitude of molecular configurations a dopant can adopt. To overcome the problem, much finer control of the functionalization chemistry needs to be developed. A few possible approaches can be envisioned. For instance, by controlling the structure of the nanotube surface coating, one may force the dopant molecule to choose a particular configuration. Sorting functionalized SWCNTs by dopant configurations is another possible route.

The ultimate system for single-photon generation is one in which precise control of light emission can be exercised. Such a capability comes down to mastering material synthesis, combined with the ability to engineer the electromagnetic environment that surrounds the quantum emitter. Together, this ensures that single photons with desired properties are funnelled into a useful optical channel that can be interfaced with other quantum optical elements and systems. With the availability of a broad range of nanotube structures and a large organic chemistry toolbox, along with a variety of nanofabrication technologies for incorporating such structures into devices, the prospects for SWCNT-hosted organic colour centres certainly look promising at this early stage of development. ❐

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OPTICAL COMMUNICATIONS

Embracing nonlinearity

An innovative data transmission protocol that effectively makes an optical fibre link linear in its behaviour is shown to benefit high-speed, long-distance optical communication operating at high signal powers.

Antonio Mecozzi

It is beyond doubt that optical communications has been the key enabling technology behind the development of the modern information-society era. The evolution of the Internet into a global phenomenon would simply not have been possible without the ability of fibre-optic links to carry an enormous amount of information per second. However, with the exponential increase of data traffic observed in the past decades, it is easy to foresee that with today's optical technologies the world of telecommunications will soon experience a dramatic shortage of capacity, which has been effectively dubbed the capacity crunch[1]. Can we avoid the predicted crisis?

One possible solution may lie with a new approach to fibre-optic data transmission called nonlinear orthogonal division multiplexing. In this issue of *Nature Photonics*, a team of researchers from Bell Labs provide an experimental demonstration of the quantitative benefits of the approach[2].

The famous capacity formula developed by the father of information theory Claude Shannon in the late 1940s states that the maximum information (the capacity) that can be reliably transmitted per unit time on a physical channel — described by linear input–output relations and impaired by additive Gaussian noise — increases with the ratio between the signal and noise powers.

In essence, this means that to increase capacity, one may either reduce the noise or increase the signal power. Reducing the noise is not a viable solution because the noise of a fibre-optic channel comes mainly from the unavoidable amplified spontaneous emission (ASE) of the optical amplifiers that compensate for the fibre loss. The noise figure of commercial amplifiers is already very close to the minimum level dictated by quantum mechanics.

Consequently, the only option for increasing capacity is to increase the optical signal power. Unfortunately, however, increasing the transmitted signal power leads to waveform distortions caused by the nonlinear dependence of the fibre refractive index on the optical power, a process known as the optical Kerr effect. These distortions lead to a signal degradation, whose origin is most easily understood when referring to the ideal case of an optical fibre with negligible chromatic dispersion.

In the absence of fibre chromatic dispersion, after propagation over a distance z, the optical field at time t, $E(t, z)$, acquires a nonlinear (NL) phase shift that depends on the input field intensity $\phi_{NL} = \gamma|E(t, 0)|^2 z$, where γ is the