laser[19–21] represents another path for serving the mid-IR spectrum. There has also been rapid progress in fibre-based mid-IR amplifiers and lasers, as exemplified here by the use of fibre-based pump and probe sources in the work of Zlatanovic and co-workers[11].

It remains to be seen whether silicon mid-IR sources and amplifiers will become the solution of choice for future mid-IR photonics. However, what is clear is that the recent interest and activities in the mid-IR regime of silicon photonics represent significant progress, giving hope for on-chip applications. After all, for chip-to-chip and intrachip optical interconnects to be fully realized, it may be necessary to compensate for signal losses through on-chip amplification. An all-optical on-chip signal processing system may also find use in dispersion mitigation and signal conditioning in future fibre-optic networks. Another potential application is the development of mid-IR amplifiers and sources for biochemical sensing and medical therapy at wavelengths that are hard to reach through other means. For such applications, both FWM and Raman techniques should be considered, and in both cases pumping in the mid-IR is preferable. ❐

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QUANTUM OPTICS

A spooky light-emitting diode

The generation of entangled photon pairs is usually a complex process involving optically driven schemes and nonlinear optics. The recent demonstration of an electrically powered light-emitting diode that is capable of this task looks set to greatly simplify experiments in the field of quantum information processing.

Val Zwiller

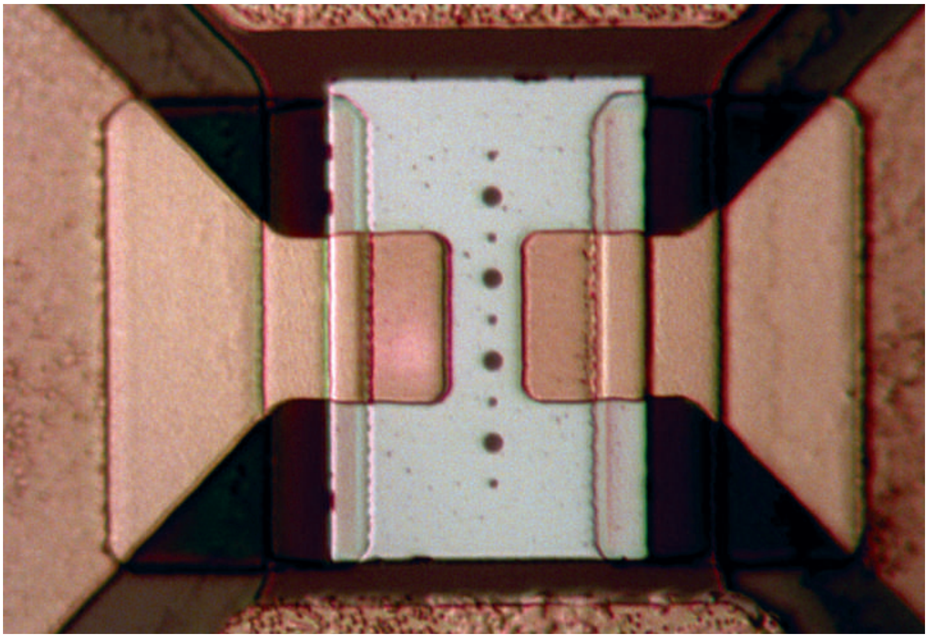
The thought experiment suggested by Einstein, Podolsky and Rosen[1] in 1935 to test the locality of quantum mechanics was experimentally demonstrated decades later using pairs of entangled photons[2,3]. In recent years, quantum entanglement has become a crucial resource for quantum information processing, creating the need for an efficient and reliable source of entangled photon pairs on demand.

The generation of polarization-entangled photon pairs has traditionally been performed with lasers and nonlinear crystals, yielding Poissonian emission statistics. This Poissonian distribution makes it impossible to deterministically generate a single entangled photon pair on demand. Other weaknesses of this technique include its very low overall energy efficiency and high complexity. Now, reporting in *Nature*, Salter *et al.* describe a quantum-dot-based LED that could be an elegant electrically driven alternative[4].

In 2000, Benson *et al.*[5] suggested the idea of using a quantum dot to generate pairs of entangled photons on demand. By populating a single quantum dot with two electrons and two holes (known collectively as a biexciton), two photons can be emitted in a cascade with an exciton as the intermediate level. Provided that the two excitons are degenerate (that is, indistinguishable in energy) and thus yield no which-path information, the two photons that are emitted will be entangled in polarization. Implementing this scheme has proved challenging because the two exciton levels are usually non-degenerate in quantum dots. The problem was first solved by Akopian *et al.*[6], who observed polarization-entangled photon pairs by energy filtering between the two exciton energy levels. Using quantum dots with small exciton fine-structure splittings, the Shields group at Toshiba research labs in Cambridge, UK, was then able to demonstrate entangled photon pair generation without filtering between the two exciton levels[7].

These first experiments used a laser to excite the quantum dot. An alternative method would be to embed a quantum dot with a small enough fine-structure splitting in a p–n junction, thus yielding a compact LED capable of generating entangled photon pairs on demand with high power efficiency and sub-Poissonian statistics. Such an LED, now realized by Salter *et al.*, could replace complex experimental set-ups with a single compact electrically pumped device (Fig. 1). In the scheme of Salter *et al.*, self-assembled InAs quantum dots were grown by molecular beam epitaxy in a microcavity tuned to the InAs quantum dot emission at 1.4 eV (wavelength of ~890 nm) and doped to form a p-i-n (p-type/intrinsic/n-type layers) heterostructure centred on the quantum dots. Electrical contacts were placed on top of the device, with small windows allowing the emission from a single quantum dot to be observed.

The researchers revealed quantum entanglement in polarization by measuring cross-correlations between the biexciton and exciton emission as a function of polarization. The experiment was



TOSHIBA EUROPE

Figure 1 | Optical microscope image of the quantum-entangled LED developed by the team of researchers from Toshiba Europe and the University of Cambridge, UK.

performed under both continuous-wave and pulsed excitation, demonstrating the ability to generate sub-Poissonian entangled photon pairs on demand through pulsed excitation. The reported rate of less than three entangled photon pair detections per second requires further improvements in extraction and collection efficiency for this technique to become widely implemented. However, new device designs such as tapered nanowires[8] have the potential to achieve very high light-extraction efficiencies, and the electrical excitation of single quantum dots in nanowires has already been demonstrated[9]. Further improvements in the overall efficiency will be achieved for devices with only one active quantum dot; a device in which all the injected current recombines in only a single quantum dot would yield the highest possible electron-to-photon conversion efficiency. Entangled LEDs could then be scaled down to submicrometre sizes, enabling extensive on-chip integration.

For the most advanced applications in quantum information processing, arrays of indistinguishable sources of entangled photon pairs will be required. Quantum indistinguishability was recently demonstrated with single photons emitted from two quantum dots[10] and also from two molecules[11]. Deterministic sources of indistinguishable entangled photon pairs will enable the implementation of quantum information processing schemes such as entanglement swapping, paving the way to quantum repeaters. However, creating arrays of indistinguishable entangled photon sources may require a more controlled system than self-assembled quantum dots, such as the pyramidal dots recently shown to generate entangled polarization photon pairs[12]. The additional advantages of the pyramidal quantum dot technique are site-controlled growth and material freedom, which could enable the generation of photon pairs at telecommunications wavelengths and thus allow long-distance quantum communication to be realized[13].

Merging quantum optics with nanoscience has once again resulted in a device with new exciting functionalities. The resulting improvements in size, alignment complexity, stability and power efficiency over existing sources of entangled photon pairs will offset the requirement for cryogenic temperatures. The challenge now is to reach generation intensities comparable to those of nonlinear crystals. ❐

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Correction

In the Technology Focus Industry Perspective 'LIDAR: Mapping the world in 3D' (*Nature Photon.* **4,** 429–430; 2010), the credit for the image on page 429 was incorrectly given to Velodyne. The image was courtesy of Mandli Communications, and should have been credited as such.

Similarly, in the Technology Focus Editorial 'A sense of diversity' (*Nature Photon.* **4,** 423; 2010), credit for the Technology Focus cover image should have been given to Mandli Communications. The HTML and PDF versions of both texts are correct.