layer, respectively. In essence, the whole illuminated area of the scattering medium behaves as a coherent focusing lens.

The experiment of Vellekoop and colleagues proves that scattering in a random medium behind a lens can be used to improve the focusing resolution to beyond the Abbe limit of the lens. The next challenge is to achieve focal spots much smaller than the wavelength of light used, and this has already been achieved for microwaves, using a random scattering medium comprised of subwavelength resonators[7]. Such developments may open up new avenues in the design of optical superlenses based on random metamaterials. ❐

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References

1. Vellekoop, I. M., Lagendijk, A. & Mosk, A. P. *Nature Photon.* **4,** 320–322 (2010).
2. Derode, A., Roux, P. & Fink, M. *Phys. Rev. Lett.* **75,** 4206–4209 (1995).
3. Blomgren, P., Papanicolaou, G. & Zhao, H. *J Acoust. Soc. Am.* **111,** 230–248 (2002).
4. Vellekoop, I. M. & Mosk A. P. *Opt. Lett.* **32,** 2309–2311 (2007).
5. Popoff, M. *et al. Phys. Rev. Lett.* **104,** 100601 (2010).
6. Yaqoob, Z., Psaltis, D., Feld, M. S. & Yang, C. *Nature Photon.* **2,** 110–115 (2008).
7. Lerosey, G., de Rosny, J., Tourin, A. & Fink, M. *Science* **315,** 1120–1122 (2007).

QUANTUM DATA PROCESSING

Pyramidal quantum dots

The use of a fabrication scheme for controlling the symmetry, uniformity and location of quantum dots has resulted in a superior source of entangled photon pairs.

David Gershoni

The building block of the emerging field of quantum information technology is the quantum bit ('qubit') which describes the quantum state of a physical system with only two levels. There are many examples of naturally occurring qubits: most common are the spins of a single electron, a single nucleus or a single atom. These are 'anchored' qubits. The polarization state of a single light particle — the photon — can be similarly described as a qubit and is often referred to as a 'flying' qubit[1].

Entanglement is an intriguing, non-classical correlation between quantum systems[2] and occurs when there is a 'which path' ambiguity and no way of knowing through which of the possible paths a process evolved. Two qubits are considered to be entangled if, and only if, their mutual state cannot be described as a product of the state of each qubit[3]. Entanglement between two and more qubits is an essential resource for quantum computing[4] and for teleportation[5]. Entangled photons are particularly attractive for applications because of their non-interacting nature and the relative ease with which they can be manipulated and steered in space[1]. Polarization-entangled photons are routinely and quite efficiently produced by nonlinear optical effects such as parametric down-conversion in a nonlinear optical crystal[6]. These sources are, however, intrinsically random in nature, whereas quantum data processing schemes require non-random, deterministic 'on demand' or 'event-ready' entangled photons[7].

Writing in *Nature Photonics*, Arun Mohan and co-workers in Switzerland have achieved a step forward in this direction[8]. In particular, they have succeeded in fabricating high-quality InGaAs/GaAs semiconductor quantum dots (SCQDs) and triggering emission of pairs of entangled photons from a large fraction of them.

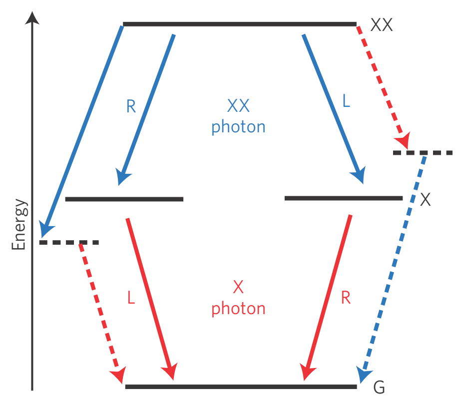

Figure 1 | A biexciton (XX) decays through the intermediate exciton (X) state to the ground (G) state by emitting two photons with opposite circular polarizations (L, left; R, right). If the exciton level is non-degenerate (dashed levels), then the two photons (dashed arrows) are collinearly polarized and the paths can be distinguished by their energies (colours). Therefore, they are not entangled. In a symmetric quantum dot the exciton level is degenerate (solid levels). The two photons (solid arrows) are cross-circularly polarized and so their decay path is not revealed by their energies. Therefore, they are entangled.

Semiconductor quantum dots (SCQDs) are nanometre-sized structures that confine charge carriers in all three dimensions. This confinement results in an atomic-like discrete energy level spectrum for the confined carriers and for this reason SCQDs are often called 'artificial atoms'. Quantum dots are of great interest for applications in quantum information processing as their fabrication can be scaled up to large numbers of devices and, being a semiconductor structure, they are fully compatible with modern microelectronics and photonics. During the past two decades, great efforts have been devoted to preparing, controlling, demonstrating and measuring devices and concepts based on semiconductor quantum dots. In particular, these systems have shown to provide optically[9] and electrically[10] driven sources of single and paired photons on demand, and are a promising source for event-ready entangled photons[11]. The Swiss team have now taken things further by developing a growth and fabrication method that improves the chances of SCQD-based devices becoming reliable sources for deterministic, polarization-entangled photons.

The notion that a cascaded emission process in a SCQD could provide a source of event-ready entangled photons was suggested by Benson *et al.*[7] ten years ago. They postulated that a biexciton (two confined electron–hole pairs) could decay by emitting two photons with opposite circular polarizations. The emission process involves two distinct decay paths via an intermediate degenerate single-exciton state (X in Fig. 1). As there is no indication by which 'path' the radiative cascade occurs, the polarizations of the resulting pair of photons should have quantum correlations, or in other words, should be entangled.

Although the scheme does indeed work, prior to the research of Mohan *et al.*, self-assembled quantum dots that had been used always suffered from slight inherent asymmetry. The problem is that this asymmetry induces splitting of the intermediate single-exciton energy levels, distinguishing between the two decay paths of the biexciton. The two emitted photons become collinearly polarized either horizontally (parallel to the major in-plane symmetry axis of the quantum dot) or vertically (perpendicularly to that axis), and their colours (energies) are fully correlated with their polarizations. As the colours provide information about the decay path by which the quantum dot relaxes, the identity of the 'path' disentangles the two photons and prevents them from being non-classically correlated (Fig. 1).

Mohan and co-workers have now partially overcome this problem by developing a growth technique for InGaAs/GaAs quantum dots that greatly improves the efficiency of generating entangled photons. The work involves two important milestones.

First, Mohan *et al.* developed a robust way of fabricating very uniform and highly symmetric quantum dots. Their dots are pyramidal in shape and offer three-fold rotational symmetry around an axis parallel to their growth direction. As a result, the splitting of the exciton energy levels is typically about an order of magnitude smaller than that in previously studied SCQDs and is comparable to its radiative widths (~1–2 μeV). This is an important prerequisite for achieving any noticeable entanglement between the polarization state of the biexciton photon and that of the exciton photon.

Second, but no less important, is that they have managed to control quite accurately the actual locations of the quantum dots. This is an attribute of their SCQD growth method, which makes use of growth in pre-etched patterned locations on the GaAs substrate surface. Accurate positioning or site control of the SCQDs opens the door to a wide range of additional advantages. Most notable is the ability to embed quantum dots within a photonic bandgap microcavity. A properly designed microcavity[12] can significantly increase the interaction between light and matter, improving SCQD performance by increasing the exciton radiative width significantly above its level splitting. This will substantially increase the degree of entanglement between the two photons in the radiative cascade.

Additionally, a properly designed microcavity will result in a substantial increase in the light harvesting efficiency of the emitted light. A truly deterministic source of single and entangled photons on demand requires a light harvesting efficiency of close to 100%. Such a high efficiency has yet to be demonstrated, but the approach of Mohan *et al.* may bring us closer to that goal. ❐

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References

1. Zeilinger, A., Weihs, G., Jennewein, T. & Aspelmeyer, M. *Nature* **433,** 230–238 (2005).
2. Einstein, A., Podolsky, B. & Rosen, N. *Phys. Rev.* **47,** 777–780 (1935).
3. Peres, A. *Phys. Rev. Lett.* **77,** 1413–1415 (1996).
4. Ekert, A. K. *Phys. Rev. Lett.* **67,** 661–663 (1991).
5. Bennett, C. H. *et al. Phys. Rev. Lett.* **70,** 1895–1899 (1993).
6. Kwiat, P. G., Waks, E., White, A. G., Appelbaum, I. & Eberhard, P. H. *Phys. Rev. A* **60,** R773–R776 (1999).
7. Benson, O., Santori, C., Pelton, M. & Yamamoto, Y. *Phys. Rev. Lett.* **84,** 2513–2516 (2000).
8. Mohan, A. *et al. Nature Photon.* **4,** 302–306 (2010).
9. Michler, P. *et al. Science* **290,** 2282–2285 (2000).
10. Yuan, Z. *et al. Science* **295,** 102–105 (2001).
11. Akopian, N. *et al. Phys. Rev. Lett.* **96,** 130501 (2006).
12. Badolato, A. *et al. Science* **308,** 1158–1161 (2005).

ULTRAFAST OPTICS

Nonlinear attraction

A new femtosecond fibre laser design combines two distinct regimes of nonlinear dynamic attraction within a single cavity to yield robust and low-noise performance.

John M. Dudley

Ultrafast science impacts nearly all areas of modern technology, and femtosecond lasers have proved themselves to be important tools in many different applications including materials processing, imaging and frequency metrology. Advances in ultrafast science have always gone hand-in-hand with the development of new ultrashort pulse lasers, but a crucial practical challenge is to make these lasers work reliably outside the laboratory in the real world. Fibre-based sources are widely considered as the solution to this problem, and a range of compact and robust femtosecond fibre lasers is now available. The propagation of short pulses in optical fibre, however, inevitably leads to high intensities, and hence learning how to manage and compensate nonlinear effects in fibre laser cavities is essential to ensure their stable operation.

Reporting in *Nature Photonics*, Bulent Oktem and co-workers introduce a new approach to deal with nonlinear effects in a fibre laser[1]. In fact, they do not attempt to avoid or compensate for nonlinearity at all; rather, they have designed a fibre laser with a cavity configuration that takes advantage of the nonlinearity to simultaneously support two different types of nonlinear shape-preserving pulses: solitons and similaritons.

Their soliton–similariton fibre laser operates around the important telecommunications wavelength of 1,550 nm and is based on two distinct branches, each of which sustains a fundamentally distinct type of nonlinear wave (Fig. 1). One branch uses standard telecommunications-grade single-mode fibre with anomalous group velocity dispersion (GVD), whereas the other branch uses a normal GVD erbium-doped fibre amplifier to provide gain. Propagation in the anomalous GVD fibre involves well-known soliton shaping dynamics, whereas propagation in the normal GVD gain fibre is fundamentally different and involves 'self-similar' amplification. The latter is a special type of nonlinear propagation that preserves the shape of a pulse even as it increases in energy while it is amplified. In particular, an input pulse to the normal GVD gain segment will evolve with distance into a pulse that has a parabolic intensity