light sources in optoelectronic circuits for communications, opens up completely new avenues of research in nanoscale sensing or simply gives us a better understanding of how light and matter interact. ❐

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QUANTUM OPTICS

Linking crystals with a single photon

Linking distant quantum memories with light has been a goal of the quantum information community for many years. A team at the University of Geneva has now demonstrated that memories made from rare-earth-ion-doped crystals can be connected using a single photon.

Steven Olmschenk

The ability to transmit quantum states over large distances is a goal that is being hotly pursued by researchers across the globe. Although distances as great as 144 km have been successfully spanned by single photons[1], connections over arbitrary distances will probably require the use of quantum memories (capable of storing quantum states) to allow repeaters to overcome the detrimental losses associated with long transmission distances.

Although simple amplification of a quantum signal using a conventional optical amplifier is ruled out by the no-cloning theorem[2], which prohibits copying an unknown quantum state, quantum memories make it possible to break the link up into several shorter segments. The deployment of quantum memories may not only enable long-distance quantum communication for ultrasecure information transfer, but might also be used to perform distributed quantum information processing (or quantum cloud computing), allowing access to computational problems that are inaccessible through classical approaches.

For these reasons, significant effort is currently being directed towards linking quantum memories with photons to establish quantum connections between distant quantum memories. Entanglement is widely viewed as an essential resource for creating such a quantum connection in both quantum communication and quantum-information processing. A particularly useful type of entanglement-creating operation is one that is 'heralded', whereby a 'heralding event' (such as the detection of a photon) signals the creation of entanglement between the quantum memories. Heralded-entanglement operations between quantum memories have been realized in a number of physical implementations, including atomic ensembles[3] and trapped atomic ions[4]. Now, writing in *Nature Photonics*, Usmani *et al.* experimentally demonstrate how a heralded single photon can create entanglement between two rare-earth-ion-doped crystals separated on the centimetre scale[5]. One of the advantages of this system is that established fabrication techniques for these solid-state devices may assist scaling for future advanced operations in quantum information.

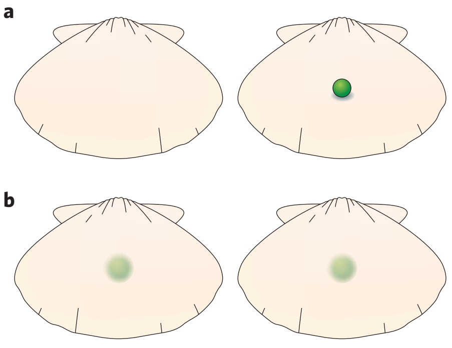

Figure 1 | Classical and quantum shell games. **a**, In a classical shell game, a single pea is hidden under one of two shells. **b**, In a quantum shell game, the pea is under both shells simultaneously in the form of a superposition — this is analogous to the form of entanglement used in the work of Usmani *et al.*

The basic form of entanglement employed by Usmani *et al.* is a bit like a quantum version of a shell game (Fig. 1). In a classic shell game, a single 'pea' is placed under one of multiple shells and the player guesses where the pea resides. The quantum version of this game would involve a single pea that is in a superposition of being under all shells simultaneously. Once a measurement is made, the quantum superposition collapses and the pea is found under one of the shells. The entangled state produced by the experiment presented in this issue of *Nature Photonics* is analogous to this situation, where a single photon replaces the pea, and crystals replace the shells.

Usmani *et al.* began by producing a pair of photons through the standard quantum-optics technique of spontaneous parametric downconversion. Because the generation of this photon pair is probabilistic, detecting one of the two photons heralds the presence of the other, thus giving researchers a guarantee that they are sending just one photon into their experiment. The latter of these photons is the 'pea' in the quantum shell game. Usmani *et al.* sent this photon to a beamsplitter and directed the two output paths towards two separate crystals (Fig. 2). The photon is absorbed by one of the crystals, where it excites one of the many optically active rare-earth ions confined therein. However, the inherent lack of information regarding which path the photon travelled — and thus by which crystal it was absorbed — results in the creation of an entangled state between the two crystals. One of the two crystals ought to contain an excitation, but the excitation is in an entangled superposition state between the two crystals — this is analogous to the pea being under both shells simultaneously. Usmani *et al.* were able to store this superposition state for up to 33 ns.

Because directly measuring the excitation of the crystal is a significant experimental challenge, Usmani *et al.* verified the entanglement by using an echo technique to write the stored entangled state back to a photon. Correlation measurements between the two paths of this re-emitted photon established a lower bound for the quality of the entanglement between the two crystals. Using these measurements, Usmani *et al.* were able to demonstrate that their single heralded photon indeed created an entangled state between the two crystals.

Of course, there are plenty of challenges that must be overcome before this system can be used to establish a large quantum network. One of the biggest challenges — one faced by all such probabilistic entangling schemes demonstrated so far — will be increasing the overall efficiency of the system, which limits the rate of entanglement generation and thus the rate of information transfer. Another necessary improvement is increasing the distance between the crystals — Usmani *et al.* employed a spacing of just 1.3 cm to avoid the use of multiple cryostats. Other issues include improving the quality of the entanglement and lengthening the storage duration of the quantum state.

However, researchers have already demonstrated impressive progress towards tackling many of these issues, including demonstrations of long-lived coherences in crystals[6] for potentially storing received information and proposed architectures to increase the distance between crystal quantum memories[7]. Moreover, the intriguing possibility of fabricating structures directly into the crystals to improve the overall efficiency of the system adds to the appeal of these solid-state devices. Combining such advances with the spatial and temporal multiplexing abilities of these crystals, which might also be used to improve the entanglement rate, will make this system a strong contender for the scalable technology needed to implement large quantum networks. ❐

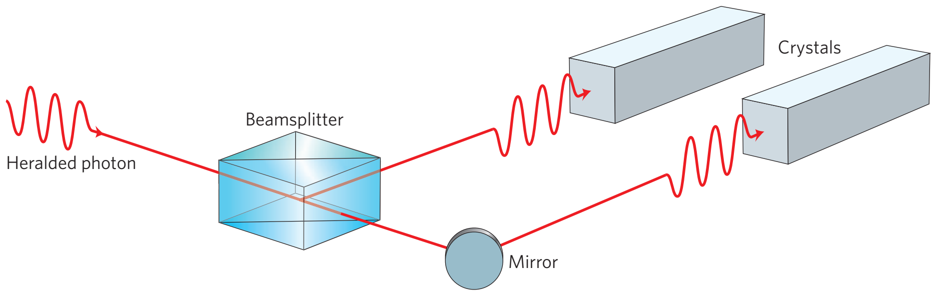

Figure 2 | Creating entanglement between two quantum memories. A heralded single photon (the 'pea') first passes through a beamsplitter. The outputs of the beamsplitter are directed to the two crystals (the 'shells'), where the photon is absorbed to produce a single excitation. The lack of information regarding the path of the photon creates an entangled state between the two crystals.

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VIEW FROM... SPIE PHOTONICS WEST 2012

Photons, neurons and wellbeing

Techniques for the targeted optical stimulation of neurons may offer new ways to tackle medical problems such as heart defects, epilepsy, Parkinson's, blindness and hearing loss.

David Pile

Using light to control biological processes is a relatively new joint research direction of the biological and physical sciences. Yet there is already a great deal of motivation for developing such technologies, as made clear from the "Photons and Neurons" sessions at SPIE Photonics West 2012, held in San Francisco, USA, on 21–26 January 2012.

Over a billion people worldwide suffer from brain disorders such as stroke, depression, migraine, epilepsy, Parkinson's, chronic pain and blindness. According to Edward Boydon, an expert on brain disorders from the Massachusetts Institute of Technology Media Lab, few of these disorders are effectively treatable by drugs or neurosurgical procedures. Furthermore, the treatments that do exist are often partial or present undesirable side effects. Part of the problem is the complexity of the dense neural circuits in the brain.

"Ideally we would be able to hone in on the precise circuits that can best contribute to the remedy of disease, and then use those circuits as drug targets, or as targets for neurosurgeons to implant electrodes to reduce symptoms," Boydon explained. "To do this, we invented a new technology that allows us to control specific cells embedded within dense neural circuits with light. We do this by exploiting the photosynthetic and photosensory proteins found in many biological species, which convert light into electrical energy."

Installing photosensory cells in a particular region of the brain modifies the neuronal cells to respond to light while leaving the surrounding cells unaffected. Boydon's team deliver the genes that encode for these proteins to targeted neurons by employing gene therapy viral vectors currently used for gene therapy trials in humans. They deliver the light by inserting compact optical probes such as optical fibres attached to small LEDs or lasers into the brain. Boydon and colleagues are now working on three-dimensional (3D) light-delivery devices — arrays of waveguides — to achieve improved control over 3D neural circuits. Light delivery methods in the field of optogenetics (the stimulation of nerve cells with light) was one of the key discussion points at the meeting.

Partrick Degenaar from Newcastle University in the UK explained that the rise of optogenetics has many exciting applications to neuroprosthesis. Future developments will require researchers to find ways of efficiently delivering light at the required intensity and depth — particularly because biological tissue is a strong scatterer